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HALON REPLACEMENT PROGRAM FOR AVIATION

Aircraft Engine Nacelle Application Phase I - Operational Parameters Study

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This report documents the work performed under Phase I - Operational Parameters Study - of the Halon Replacement Program for Aviation for the Aircraft Engine Nacelle Application. Phase I is the first of a three-phase program to determine a replacement for Halon 1301 in aircraft engine nacelle applications. The objective of Phase I testing was to determine which parameters, in an aircraft engine nacelle fire, most influence the amount of agent needed to extinguish that fire. Of the 15 parameters tested, the factors which were most influential in an engine nacelle fire were: Surface Temperature, Fuel Temperature, Pre-Burn Time, Agent, Fuel Type, Cross-Sectional Area, and Air Temperature. These factors were recommended for inclusion in Phase II of the overall test program.

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GLOSSARY

amp	ampere
ASC	Aeronautical Systems Center
ASRF	Aircraft Survivability Research Facility
cfm	cubic feet per minute
degrees of freedom	statistical reference to the number of independent terms used to estimate the variability in the data from that variable
DOX	Design of Experiments
° F	degrees Fahrenheit
FAA	Federal Aviation Administration
fps	feet per second
HP	Hewlett Packard
Hz	Hertz
KHz	Kilohertz
kts	knots
mm	millimeter
MSDS	Material Safety Data Sheets
NIST	National Institute of Standards and Technology
psig	pounds per square inch gage
PT	pressure transducer
residuals	statistically, a residual at a given observation is (the observed response value from the experimental data) minus (the predicted response value from the fitted linear model)
SURVIAC	Survivability/Vulnerability Information Analysis Center
T2	Technology Transition
TC	thermocouple
V	volt
WL	Wright Laboratory
WPAFB	Wright-Patterson Air Force Base

PREFACE

This research and development task was sponsored by the Air Force, Army, Navy, and Federal Aviation Administration. Data Management activities for this effort were performed as Task 94-05 under contract DLA900-90-D-0424. This final technical report summarizes work performed in Phase I of the Halon Replacement Program for Aviation, Aircraft Engine Nacelle Application, from October 1992 to September 1993. This task was administered under the technical direction of Mr. J. Michael Bennett (WL/FIVS), Wright-Patterson Air Force Base, Ohio.

EXECUTIVE SUMMARY

The Clean Air Act Amendments (CAAA) of 1990 and U.S. Environmental Protection Agency (EPA) rules limit U.S. production of ozone depleting substances (ODS). These actions carry out the United States obligations under the "Montreal Protocol on Substances that Deplete the Ozone Layer," an international treaty ratified by the Senate in December 1988, limiting global production of such chemicals. Subsequent international and national legislation has dictated the phase-out of the production of these chemicals.

As a result of these actions, the U.S. Air Force made a decision in 1992 to develop a "nonozone depleting solution" for on-board aircraft fire extinguishing by 1995. This timeline was dictated by the program schedule of the F-22 fighter, so that this alternative solution could be considered for implementation. A program for evaluating and identifying alternative extinguishants that would be commercially available was developed by the Air Force's Wright Laboratory. This program - The Halon Replacement Program for Aviation - was subsequently expanded in scope to include the requirements of all U.S. military and commercial aircraft engine nacelle and military dry bay applications and was jointly sponsored by the U.S. Air Force, Navy, Army, and Federal Aviation Administration. A Department of Defense Halon Alternatives Steering Group was established to oversee this and other similar programs.

A Small Business Innovative Research (SBIR) effort funded by Wright-Patterson Air Force Base investigated a total of 600 chemicals with a configuration similar to the halons as potential replacements. These potential replacement chemicals were investigated for toxicity, physical traits, and fire-fighting effectiveness to determine which had the potential to meet aviation requirements. It was determined that ten chemicals had characteristics acceptable for aircraft use and the capability to generate the necessary supplemental data within the required program timelines. To these ten, the Air Force added two, which were suggested from other data sources. A screening program to reduce this list of 12 to the three best for full-scale testing was conducted by the National Institute of Standards and Technology (NIST). Concurrently with this NIST testing, Phase I of the Halon Replacement Program for Aviation was conducted at Wright Laboratory.

This final report documents the work performed under Phase I - Operational Parameters Study - of the Halon Replacement Program for Aviation, Aircraft Engine Nacelle Application. This joint program was designed to find a replacement chemical extinguishant for halon as a fire extinguishant on-board military and commercial aircraft. There are two applications considered under this program - engine nacelles and dry bays. This report deals with the engine nacelle application. The concern for engine nacelle fires centers around the space between the engine cowling and the engine core, where fuel lines, hydraulic lines, and other protuberances and equipment are affixed to the core. An analogous series of tests was also conducted to determine a halon replacement for the dry bay application. That work was documented in a similar series of reports.

Halons are being replaced because they have been found to deplete the earth's protective stratospheric ozone layer. Stratospheric ozone depletion is predicted to have a significant adverse global impact on human health, climate, and natural environmental systems. Accordingly, international and national legislation has dictated the phase-out of the production of these substances and production has ceased as of 1 January 1994. Halons are important because they have been in use as fire extinguishants in military and commercial aircraft since the late 1940s. After many years of operational experience, Halon 1301 (CF_3Br) emerged as the dominant extinguishant for aircraft. This is due primarily to the wide range of applications to which Halon 1301 is suited. However, increasing environmental concerns with ozone depletion have resulted in a mandate to discontinue its use in new systems, as well as other halons used as fire extinguishants.

There are several important considerations in replacing halon in aircraft fire protection systems. The most obvious among these is the weight and volume of the extinguishant and of the delivery equipment. Since there are severe weight and space limitations on aircraft systems, engineers may be forced to compromise fire suppression capability to comply with a restriction on system weight. This could cause a significant decrease in aircraft and crew member survivability. These were some of the issues considered in the program.

Phase I - Operational Parameters Study - was the first of a three-phase full-scale live-fire test program to determine a replacement for halon in engine nacelle applications. The objective of Phase I testing was to determine which parameters (factors) in an aircraft engine nacelle fire most influence the amount of extinguishant needed to extinguish that fire. The parameters that were found to be significant were used in Phase II to evaluate three potential replacements for Halon 1301. The three potential replacement extinguishants were selected by a Technology Transition (T2) team consisting of members from the Air Force, Army, Navy, the Federal Aviation Administration (FAA), and industry. The T2 team made their selections based on the results of extinguishant screening testing conducted by the National Institute of Standards and Technology (NIST) on 12 possible extinguishants and the results of Phase I testing conducted at Wright Laboratory. The NIST testing is documented in NIST SP 861, *Evaluation of Alternative In-Flight Fire Suppressants for Full Scale Testing in Simulated Aircraft Engine Nacelles and Dry Bays*, April 1994. The NIST testing was conducted concurrently with the Wright Laboratory Phase I testing.

In Phase II - Operational Comparison of Selected Extinguishants - the three extinguishants identified as most promising from the extinguishant screening testing conducted by NIST and selected by the T2 team were tested using the parameters determined in Phase I. The outcome of Phase II was the selection of the best engine nacelle extinguishant. This extinguishant was then used for Phase III testing.

Phase III - Establishment of Design Criteria Methodologies - was conducted in FY95. Phase III established design criteria for the new extinguishant in the engine nacelle application. The outcome of this phase was design equations for use in sizing fire-extinguishing systems based on the new extinguishant.

Through discussions with leading experts in the field of aviation fire protection, 19 previously identified aviation fire parameters relating to the engine nacelle were narrowed to the 16 parameters (factors) which were felt to be the most influential in determining the quantities of extinguishant necessary for engine nacelle fire extinguishment (response variable). Design of experiments (DOX) methodology was used to reduce the potential number of test cases from well over 32,000 to a more manageable 32. Two extreme settings were selected for each of the parameters (factors) for testing. The parameter "Extinguishant" was included in this group in order to measure the differential impact of a gaseous versus liquid type of extinguishant in the effects of fire zone parameters on the amount of extinguishant required. This parameter is not meant to recommend the extinguishant that was to be selected as the outcome of Phase II of the program. Halon 1301 and HFC-227ea were selected as the settings for this parameter (factor) because they represent extinguishants which have significantly different physical characteristics and suppress fires with different mechanisms, as discussed in Section 3.1.4. These 16 parameters (factors) and the values of the two settings for each are presented in the following table.

Table 1. Phase I Parameters and Settings

PARAMETER	SYMBOL	LOW SETTING	HIGH SETTING
Extinguishant	EXTNGT	HFC-227ea	Halon 1301
Extinguishant Discharge Location	ALOC	Side	Top
Extinguishant Distribution (either use of a simple distribution tube or "dumped" directly into the outer nacelle)	DIST	Dump	Dist Tube
Extinguishant Bottle Temperature	BTMP	-20° F	160° F
Ventilation Air Pressure	APRS	14.5 psia	17.0 psia
Ventilation Air Temperature	ATMP	100° F	275° F
Extinguishant Bottle Pressure	BPRS	400 psi	800 psi
Clutter (simulated by ribs protruding from core and nacelle)	CLUT	1-inch high rib	2-inch high rib
Configuration (simulating longer or shorter nacelle)	CONF	Short (123 inches)	Long (170 inches)
Clearance (distance between outer nacelle and engine core)	CLEAR	6 inches	12 inches
Fire Location in Nacelle	LOCA	Bottom	Top
Fuel	FUEL	MIL-H-83282	JP-8
Fuel Temperature	FTMP	100° F	200° F (83282) 325° F (JP-8)
Internal Ventilation Air Mass Flow Rate	INTE	1.25 lb/s	2.75 lb/s
Preburn Time	PREB	5 sec	20 sec
Surface Temperature	STMP	175° F	1300° F

These parameters were arranged in a Plackett-Burman L-32 Matrix. The Plackett-Burman two-level fractional factorial design was used for the test series to allow one to study the effects of the 16 factors and interactions of pairs of factors using only 32 test runs, as opposed to 2^{16} combinations of factors. The mass of extinguishant needed to extinguish the fire was the response variable.

A series of baseline tests was conducted prior to gaseous extinguishant testing to ensure a fire could be achieved and extinguished in every set of matrix conditions. Baseline tests were conducted with fire extinguisher parameters, fire quality parameters, various fixtures, and airflow parameters. In addition, checklists were developed which would ensure that the test procedures would be easily and accurately duplicated in order to protect the integrity of the data for this test series.

All tests were performed at the Aircraft Engine Nacelle Fire Test Simulator (AENFTS) located at Wright-Patterson Air Force Base (WPAFB), Ohio. The AENFTS is a ground test facility designed to simulate the fire hazards which exist in the annular compartment around an aircraft engine, and to test the effectiveness of the methods used to prevent, detect, and extinguish fires in that area. This fixture can simulate a full 360° airflow field and has a realistic helical extinguishant distribution.

Initially, the test data were analyzed using Yates Algorithm to calculate effective size and sum of squares for each factor and interaction between factors. The sum of squares was then expressed as a percent of total variability. This ratio represents the amount of variability in the response variable explained by the factor. The larger this ratio is for any factor, the stronger the indication from the data that the effect of that factor on the response variable is of sufficient size to stand out from the experimental error, or noise. The factors with the largest percent of variability explained were:

- Surface Temperature - 26%
- Fuel Temperature -15%
- Preburn Time - 6%
- Extinguishant - 5%
- Fuel - 5%
- Clearance - 4%
- Air Temperature - 4%

Some two-factor interactions also explained a substantial portion of the variability. This means a change in the parameter settings of these factors in combination significantly affects the response variable - the amount of extinguishant required to extinguish the fire.

These data were then logarithmically transformed, which is common statistical practice when the range of the response variable exceeds one order of magnitude (10X). Similar analysis of the transformed data confirmed that the factors with the largest variability explained were:

- Surface Temperature - 34%
- Extinguishant - 14%
- Clearance - 12%

The logarithmic transformation reduced the impact of the other parameters below 4% of the total variability and also reduced the importance of the two-factor interactions.

These three factors - Surface Temperature, Extinguishant, Clearance - were therefore recommended for inclusion in the Phase II Test Matrix. The inclusion of the parameters Fuel Temperature, Air Temperature, Preburn Time, and Fuel were also considered based on an evaluation of their impact in the engine nacelle fire phenomenon.

It is also recommended that the reignition phenomenon be studied in greater depth. Testing conducted during this phase of the overall test program has uncovered the problems associated with keeping a fire suppressed after the extinguishant has been discharged and fuel continues to impinge on hot surfaces. Post-discharge fuel flow time - the maximum length of time fuel can continue to flow after the release of the maximum amount of extinguishant available and still not have reignition - needs to be investigated in greater detail for various types of fuel.

1.0 INTRODUCTION

The Clean Air Act Amendments (CAAA) of 1990 and U.S. Environmental Protection Agency (EPA) rules limit U.S. production of ozone depleting substances (ODS). These actions carry out the United States obligations under the "Montreal Protocol on Substances that Deplete the Ozone Layer," an international treaty ratified by the Senate in December 1988, limiting global production of such chemicals. Subsequent international and national legislation has dictated the phase-out of the production of such chemicals. In response, industry producers have ceased production as of 1 January 1994. Other substances are likely to be added in the future. These restrictions were put in place because of data showing that the atmospheric chlorine loading caused by these chemicals correlates to depletion of the earth's protective stratospheric ozone layer. Stratospheric ozone depletion is predicted to have a significant adverse global impact on human health, climate, and natural environmental systems.

Some of the most important ODS chemicals are the halons, especially Halon 1301. The importance of halons derives from the fact they are used as the primary fire-extinguishing chemical for all aviation use, including military and civilian aircraft, for engine nacelle and military dry bay protection. The concern for engine nacelle fires centers around the space between the engine cowling and the engine core, where fuel lines, hydraulic lines, and other protuberances and equipment are affixed to the core and can rupture or leak fuel and be ignited by sparks or hot engine surfaces.

Halons have been used as fire extinguishants in military and commercial aircraft since the late 1940s. After many years of operational experience, Halon 1301 (CF_3Br) emerged as the dominant extinguishant for aircraft (with some Air Force use of Halons 1202 and 1011). This is due primarily to the wide range of applications to which Halon 1301 is suited, as well as toxicity and efficiency. However, increasing environmental concerns with ozone depletion have resulted in a mandate to discontinue its further implementation.

A decision was made by the U.S. Air Force in 1992 to develop a "nonozone depleting solution" for on-board aircraft fire extinguishing by 1995. This timeline was dictated by the program schedule of the F-22 fighter, so that this alternative solution could be considered for implementation. A program for evaluating and identifying alternative extinguishants that would be commercially available at that time was developed by the Air Force's Wright Laboratory. This program - The Halon Replacement Program for Aviation - was subsequently expanded in scope to include the requirements of all U.S. military and commercial aircraft engine nacelle and dry bay applications and was sponsored by the U.S. Air Force, Navy, Army, and Federal Aviation Administration. A Department of Defense Halon Alternatives Steering Group was established to oversee this and other similar programs.

A Small Business Innovative Research (SBIR) effort funded by Wright-Patterson Air Force Base investigated a total of 600 chemicals with physical properties similar to the halons as potential replacements. These potential replacement chemicals were investigated for toxicity, physical traits, and fire-fighting effectiveness to determine which had the potential to meet aviation requirements. It was determined that ten chemicals had characteristics acceptable for aircraft use and the capability to generate the necessary supplemental data to potentially field such chemicals within the required program timelines. To these ten, the Air Force added two from other data sources. A screening program to reduce this list of 12 to the three best for full-scale testing was conducted by the National Institute of Standards and Technology (NIST) under the direction of Wright Laboratory. Concurrently with this NIST testing, Phase I of the Halon Replacement Program for Aviation began at Wright Laboratory. Phase I testing was intended to identify the fire zone parameters most relevant to sizing fire extinguishing systems.

There are several important considerations in replacing halon in aircraft fire protection systems. The most obvious among these are the weight and volume of the extinguishant and of the delivery equipment. Since there are severe weight and space limitations on aircraft systems, engineers may be forced to compromise fire suppression capability in order to meet a restriction on system weight. This could cause a significant decrease in aircraft and pilot safety and survivability. These were some of the issues addressed in this program.

This final report documents the work performed under Phase I - Operational Parameters Study - of the Halon Replacement Program for Aviation for the engine nacelle application. This is the first of a three-phase program to select an extinguishant to replace Halon 1301 in aircraft fire suppression systems. The purpose of this testing was to define the aircraft fire zone factors which most influence the amount of extinguishant required to extinguish an aircraft engine nacelle fire. The factors found to be significant were used in Phase II to evaluate three potential replacements for Halon 1301. The three potential replacement extinguishants were selected by a Technology Transition (T2) team consisting of members from the Air Force, Army, Navy, Federal Aviation Administration (FAA), and industry. The T2 team made their selections based on the results of extinguishant screening testing conducted by NIST on the 12 possible extinguishants and the results of Phase I testing conducted at Wright Laboratory. The NIST testing is documented in NIST SP 861, *Evaluation of Alternative In-Flight Fire Suppressants for Full Scale Testing in Simulated Aircraft Engine Nacelles and Dry Bays*, April 1994. The NIST testing was conducted concurrently with the Wright Laboratory Phase I testing.

Through discussions with leading experts in the field of aviation fire protection, 19 previously identified aviation fire zone parameters (factors) were narrowed to the 16 which were felt to be the most influential in determining the quantity of extinguishant necessary for engine nacelle fire extinguishment. Two extreme but realistic operational settings were selected for each of the parameters for testing. These parameters and their settings are presented in Table 1-1.

In this test program, the quantity of extinguishant necessary to extinguish a given fire is referred to as the response variable. Statistical Design of Experiments (DOX) methodology was used to reduce the potential number of test configurations from well over 32,000 to a more manageable 32. Two settings were selected for each of the parameters for testing. A Plackett-Burman two-level fractional factorial design was used for the test series to allow one to study the effects of the 16 factors and interactions of pairs of factors using only 32 test runs, as opposed to 2^{16} combinations of factors.

All testing was performed by the Survivability and Safety Branch of Wright Laboratory (WL/FIVS) using the Aircraft Engine Nacelle Fire Test Simulator (AENFTS or AEN) located at Wright-Patterson AFB, OH. The AEN is a ground test facility designed to simulate the fire hazards which exist in the annular compartment around an aircraft engine and to test the effectiveness of the methods used to prevent, detect and extinguish fires in that area. This fixture can simulate a full 360° airflow field and allows a realistic helical extinguishant distribution. The zone volume was adjusted by a wide or narrow internal insert that represented the engine casing. The outer dimension remained constant. The compartment configuration (basically nacelle length) was controlled by placing the extinguishant release inlet at two different locations within the nacelle. A standard clutter configuration, composed of longitudinal and circumferential ribs of varying height around the outer nacelle interior and engine casing exterior, was used around the fire zone to act as a flame holder. Removable clutter was used upstream to hinder extinguishant distribution and generate realistic airflow paths. Engine case hot surfaces were achieved by means of an electrically heated panel. Air delivery and conditioning allow for the simulation of atmospheric and above-atmospheric test pressures. In addition, controllable heating of the air was provided by duct heaters located upstream.

Table 1-1. Phase I Parameters and Settings

PARAMETER	SYMBOL	LOW SETTING	HIGH SETTING
Extinguishant Discharge Location	ALOC	Side	Top
Extinguishant Distribution (either use of a simple distribution tube or "dumped" directly into the outer nacelle)	DIST	Dump (no distribution tube)	Distribution Tube
Extinguishant Bottle Temperature	BTMP	-20° F	160° F
Extinguishant Bottle Pressure	BPRS	400 psi	800 psi
Clutter (simulated by ribs protruding from core and nacelle)	CLUT	1 inch high rib	2 inch high rib
Configuration (simulating longer or shorter nacelle)	CONF	Short (123 inches)	Long (170 inches)
Clearance (distance between outer nacelle and engine core)	CLEAR	6 inches	12 inches
Surface Temperature	STMP	175° F	1300° F
Extinguishant	EXTNGT	HFC-227ea	Halon 1301
Fire Location in Nacelle	LOCA	Bottom	Top
Fuel	FUEL	MIL-H-83282 (hydraulic fluid)	JP-8
Fuel Temperature	FTMP	100° F	200° F (83282) 325° F (JP-8)
Internal Air Mass Flow Rate	INTE	1.25 lb/s	2.75 lb/s
Preburn Time	PREB	5 sec	20 sec
Ventilation Air Pressure	APRS	14.5 psia	17.0 psia
Ventilation Air Temperature	ATMP	100° F	275° F

A series of baseline tests was conducted prior to gaseous extinguishant testing to ensure that a fire could be achieved and extinguished under every set of matrix conditions. Baseline tests were conducted with fire extinguisher parameters, fire quality parameters, various fixtures, and airflow parameters. In addition, checklists were developed which would ensure that the test procedures would be easily and accurately duplicated in order to protect the integrity of the data for this test series.

2.0 TEST OBJECTIVE

The objective of this test series was to determine which parameters in an aircraft engine nacelle fire most influence the amount of extinguishant needed to extinguish that fire. The parameters that were found to be significant were used in Phase II of the Halon Replacement Program for Aviation to evaluate potential replacement extinguishants for Halon 1301.

3.0 APPROACH

Table 3-1 lists a number of fire science parameters which are considered to be important in aircraft engine nacelle fires. To the right of each parameter is the mechanism by which it influences the characteristics of an engine nacelle fire. These fire science parameters are not necessarily independent. For instance, the internal airflow rate depends on the volume size/configuration and the internal air velocity.

Table 3-1. Fire Science Parameters

PARAMETER	MECHANISM
Extinguishant (Bottle) Fill Pressure	Discharge rate
Extinguishant Bottle Temperature	Extinguishant liquid/vapor state, evaporation
Extinguishant Properties	Vaporization, propagation, extinguishant concentration
Air Pressure	Burn rate, flame stability, reaction rate, mixing
Air Temperature	Fuel residence times, burning reaction rates, extinguishant evaporation
Air Velocity	Extinguishant/fuel residence time, vortex effects, fuel/air mixture
Bottle Throat Size/ Configuration	Discharge rate
Fire Zone Configuration	Flame spread /suppression/propagation characteristics
Fire Zone Surface Temperature	Pyrolysis/ignition
Fuel Flow Rate	Combustion rate, fuel/air ratio, fuel spread, heat output
Fuel Pressure	Droplet character
Fuel Temperature	Volatility, flammability
Fuel Velocity	Mixing, evaporation
Ignition Source	Initial fire intensity, and spread
Preburn Time	Fire size, temperature and hot surface creation
Volume Size/Configuration	Extinguishant dilution, flame spread and fire location

Through discussions with leading experts in the field of aviation fire protection, these factors were narrowed to the 16 parameters, shown in Table 3-2, for study in the evaluation of their influence upon the quantity of extinguishant necessary for extinguishment of engine nacelle fires. Two extreme but realistic levels were chosen for each of these parameters (factors). The settings chosen for each level were based upon data collected by the Survivability/Vulnerability Information Analysis Center (SURVIAC) on actual aircraft operating conditions for these parameters, from data obtained from initial baseline tests requiring constraint of initial parameter extremes, and some limitations due to test facility constraints. The two level settings of Short and Long for the parameter Configuration (CONF) refer to the two different locations within the nacelle from which the extinguishant was released and were measured from the two extinguishant release points to the downstream flange.

Table 3-2. Phase I Parameters and Settings

FACTOR	SYMBOL	LOW SETTING	HIGH SETTING
Extinguishant	EXTNGT	HFC-227ea	Halon 1301
Extinguishant Discharge Location	ALOC	Side of Nacelle	Top of Nacelle
Extinguishant Distribution (either use of a simple distribution tube or "dumped" directly into outer nacelle)	DIST	Dump (no distribution tube)	Distribution Tube
Extinguishant Temperature	BTMP	-20° F	160° F
Air Pressure	APRS	14.5 psia	17.0 psia
Air Temperature	ATMP	100° F	275° F
Extinguishant Bottle Pressure, at Room Temperature	BPRS	400 psi	800 psi
Clutter (simulated by ribs protruding from core and nacelle)	CLUT	1-inch high rib	2-inch high rib
Configuration (simulating longer or shorter nacelle)	CONF	Short (123 inches)	Long (170 inches)
Clearance (distance between outer nacelle and engine core)	CLEAR	6 inches	12 inches
Fire Location	LOCA	Bottom	Top
Fuel	FUEL	MIL-H-83282	JP-8
Fuel Temperature	FTMP	100° F	200° F (83282) 325° F (JP-8)
Internal Air Mass Flow Rate	INTE	1.25 lb/s	2.75 lb/s
Preburn Time	PREB	5 sec	20 sec
Surface Temperature	STMP	175° F	1300° F

Baseline tests were conducted to ensure consistently extinguishable fires could be maintained. For each test, a fire had to be produced and also be extinguished in order to maintain the DOX test methodology.

A Plackett-Burman two-level fractional factorial design was used for this test series. This type of design allows one to study the effects of 16 factors and interactions of pairs of factors using only 32 test runs. The trade-off is that interactions of more than two factors in this design are "confounded," or indistinguishable from main factors. Two-factor interactions are not confounded with main factors. This is not a problem if the multifactor (more than two) interactions are negligible, but for this test series it was desirable to at least consider the significant two-factor interactions. Significant interactions among three or more variables are extremely rare in most cases.

The most difficult consideration in the DOX design was the measurement of the response variable - amount of extinguishant to extinguish the fire. This was actually an input to determine if the selected quantity extinguished the fire or not, rather than a direct output measurement during the conduct of the test.

To address this problem, a bracketing procedure was devised (Figure 3-1) which uses an iterative process to narrow down the amount of extinguishant required to extinguish the fire. In all tests, a minimum of four iterations was used, each adjusting the quantity of extinguishant

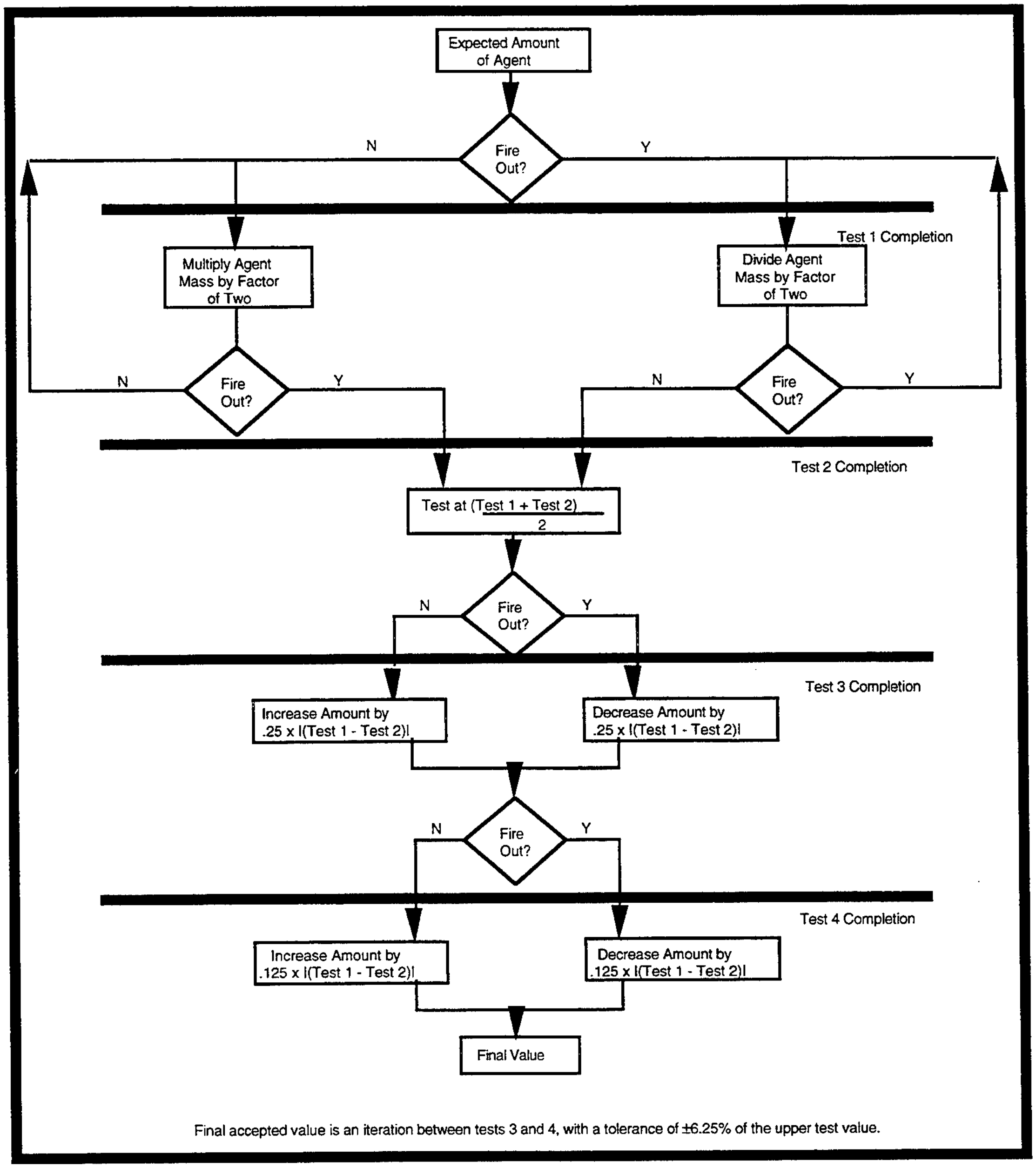

Figure 3-1. Bracketing Procedure

used, in order to determine the threshold of extinguishant mass. This methodology provided an uncertainty of ±6.25%.

3.1 Test Article Configuration

3.1.1 Aircraft Engine Nacelle Fire Test Simulator

The evaluation of the replacement fire extinguishants for the aircraft engine nacelle application was performed in the AEN located at WPAFB, OH. The AEN is a ground test facility designed to simulate the fire hazards which exist in the annular compartment around an aircraft engine, and to test the effectiveness of the methods used to prevent, detect, and

extinguish fires in that area. This facility includes air delivery and conditioning equipment designed to simulate engine compartment ventilation air flow, a test fixture within which fire testing may be safely conducted, and an exhaust system which can cool the combustion products and scrub them sufficiently to allow their release into the atmosphere. Electrical heaters were used during the program to provide a hot area on the engine simulator insert surface.

3.1.2 Engine Nacelle Configuration

An adjustable test fixture (Figure 3-2) was designed and fabricated for the AEN and placed "on line" in March 1994. The goal of the new fixture was to simulate a full 360° airflow field and thus permit a realistic helical extinguishant distribution. The parameter Clearance (CLEAR) was adjusted by using a 24-inch diameter or 36-inch diameter internal insert that represented the engine casing. The outer diameter remained constant at 48 inches. The parameter Configuration (basically nacelle length) was varied by placing the extinguishant release inlet at two different locations within the nacelle. A standard clutter configuration was used around the fire zone to act as a flame holder (Figure 3-3), which consisted of a rib on the engine casing just upstream of the fuel release tube and igniter to stabilize the flame, and a 2-inch tube downstream of the fuel igniter which represented engine plumbing and allowed the flame to attach and heat. Removable clutter (also consisting of ribs alternating on the nacelle wall and engine casing every 12 inches and varying in height from 1 to 2 inches) was used upstream to hinder extinguishant distribution.

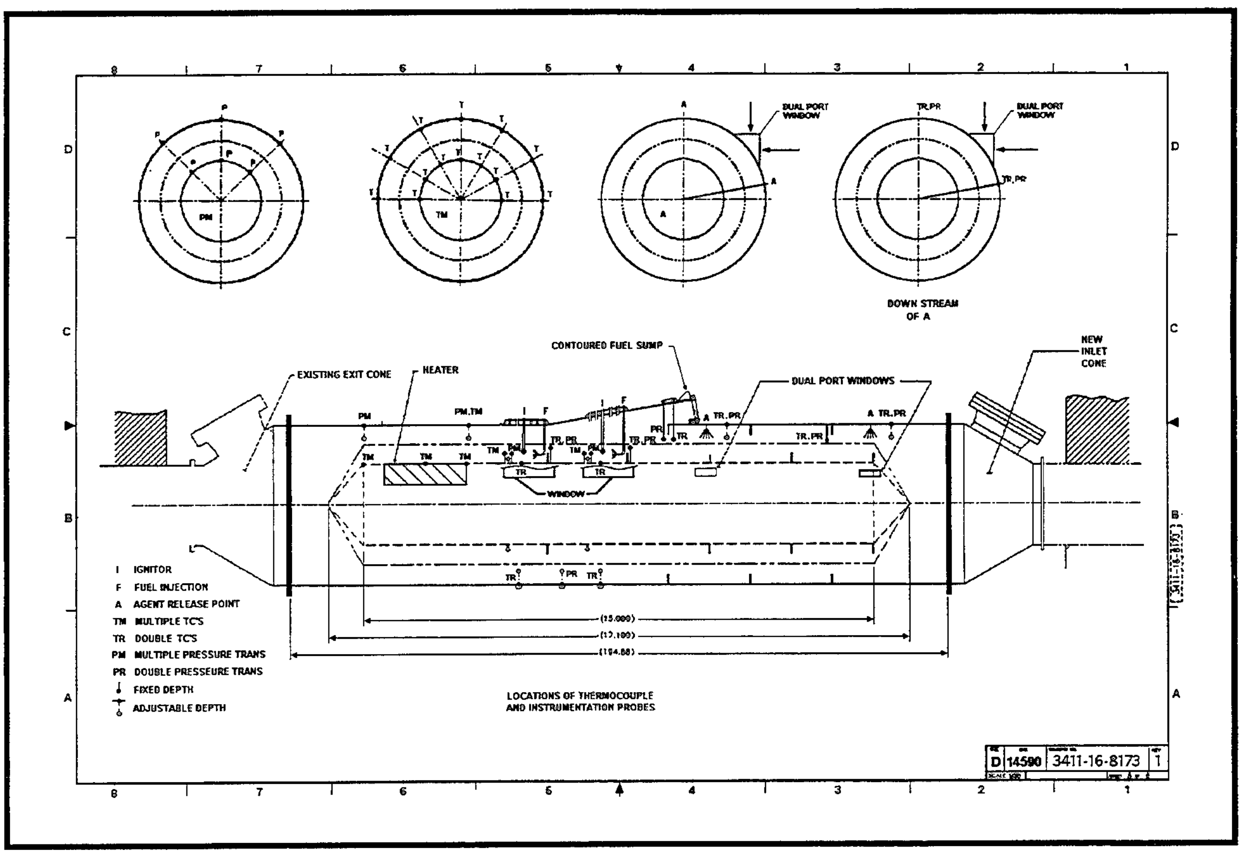

Figure 3-2. Adjustable Test Fixture

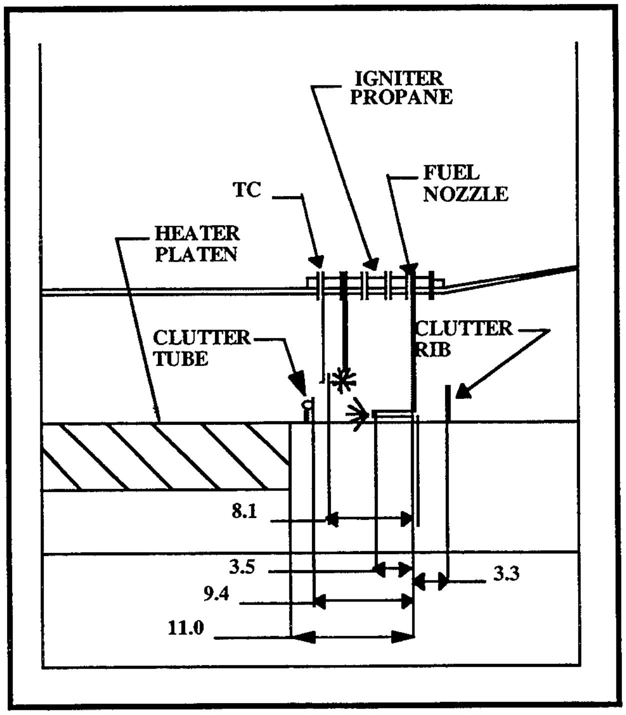

Figure 3-3. Close View of Clutter Around Fire Point

An electric heater platen was used to create an "engine hot spot" at the downstream end of the engine core. The platen was approximately 30 inches long, with a 100° arc on the insert surface. The temperature is "set point" controlled at up to 1500° F.

3.1.3 Extinguishant Conditioning and Delivery

Extinguishants are delivered to the nacelle fire from a cylindrically-shaped, high pressure bottle which is equipped to either heat or chill the extinguishant. The bottle is also designed for variable volume to accommodate the various quantities of extinguishant desired. The bottle was adjusted for each test to provide a 50% liquid fill density, which is common for most aircraft.

Heating of the extinguishant was accomplished with several electric band-type heating units mounted around the outside of the cylinder. The heaters were "set point" controlled and were effective for heating and maintaining the extinguishant up to 200° F.

For cooling, the bottle was equipped with a flat-sided "jacket" enclosure which was filled with dry ice. The temperature of dry ice was -127° F; therefore, in order to maintain the cold temperature at a known fixed point such as -55° F, the band heaters were utilized to hold the desired temperature.

The volume of the extinguishant chamber was controlled by a floating piston which could be placed and maintained at any vertical location in the extinguishant bottle. Spacer rings were used above the piston to maintain the piston location. The extinguishant was charged and delivered from the bottom of the vertically mounted cylinder, which could accommodate from 1 ounce to 24.5 pounds of extinguishant. The charging gas was always nitrogen.

Injection into the fire location in the nacelle was through a standard nozzle configuration as typically used on aircraft. A simulation of a "Y"-shaped distribution technique (See Figure

3-4), pointed downstream, was used for half of the tests to assess its influence, and the other half of the tests simply dumped the extinguishant through the side of the outer nacelle with no control of distribution. The injection location could be varied at two axial locations in the nacelle chamber.

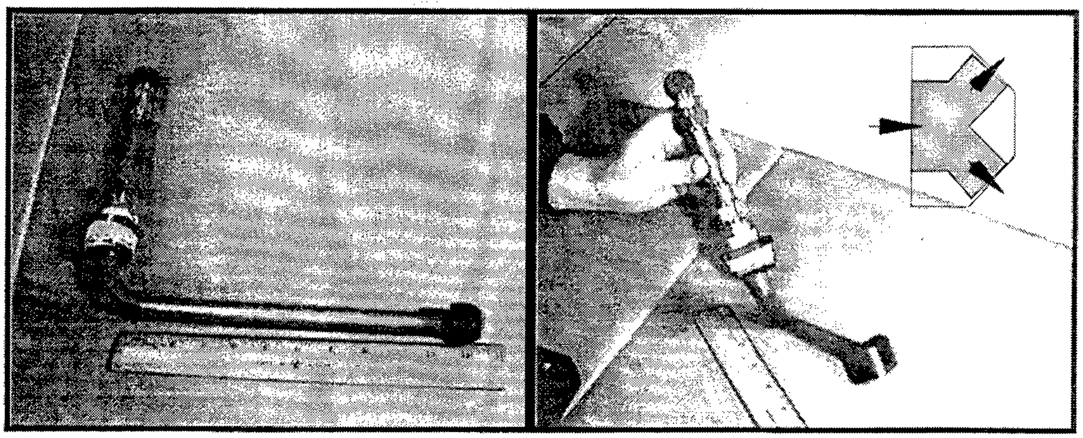

Figure 3-4. Y-Shaped Distribution Tubing

3.1.4 Extinguishants

The two extinguishants chosen for gaseous extinguishant testing were Halon 1301 and HFC-227ea. These extinguishants were chosen because their extinguishing mechanisms are radically different from one another. Halon 1301 extinguishes fires by both physical and chemical means. It physically suppresses a fire by diluting and cooling and chemically suppresses by reacting with the intermediate combustion products to break down the combustion process. In contrast, HFC-227ea has less volatility, a higher boiling point, and is more likely to be released as a liquid at lower air temperatures. Its primary fire-extinguishing mechanism is physical in nature. Its high specific heat causes it to absorb the energy of the fire. HFC-227ea was chosen as the extreme compared to halon instead of perfluorohexane (as originally intended) because, although it had a higher boiling point, it could not demonstrate adequate distribution to fires a great distance from the release point to assure extinguishing under those test conditions.

3.1.5 Airflow

Air delivery and conditioning allowed for the simulation of test pressure conditions of atmospheric pressures. In addition, controllable heating and cooling of the air were provided. The inlet air supply originated from two sources: (1) an air blower with a maximum capacity of 8,780 SCFM (11.2 pounds per second) and (2) a high pressure blow-down system with a storage capacity of 8,800 pounds of air at 2,000 psig. A flow control and vent by-pass system was used to control airflow to the engine nacelle. Standard commercial-type controllers were used to control the blower airflow. The airflow controller system consisted of a differential pressure/current transmitter, controller, current/pneumatic transducer, and a 24-inch butterfly valve with pneumatic actuator and positioner.

The air exhaust subsystem included those components downstream of the nacelle transition. Major components include the 24-inch piping from the nacelle outlet to the 10 and 24-inch butterfly valves, the 10-inch butterfly valve at the ejector inlet, the 24-inch atmospheric throttling butterfly valve, the ejector, the adaptive piping for the 10 and 24-inch pipe merging and enlarging to the 48-inch pipe, a water quencher/sump section, the 48-inch exhaust stack, a

scrubber bypass valve, the scrubber with recirculating water pump, scrubber-to-fan ducting (42-inch), and a centrifugal exhaust fan with outlet ducting. A water treatment system, which was located at ground level, accepts liquids pumped from the quench/sump section and also liquids which drain or overflow from the scrubber. In addition, combustibles are separated from the water/chemical solution through a series of baffles in the water treatment tank where quality is sensed for monitoring in the control room. Accumulated combustibles are manually drained into the facility waste fuel sump, and the water/chemical solution was recirculated until the water quality is on the verge of being chemically unacceptable, at which time the solution is expelled into the base sanitary sewer system.

3.1.6 Data Requirements

The primary data requirements were whether the fire was extinguished (observed visually and recorded) and the mass of the extinguishant required to extinguish the fire. These two data items established the measure of effectiveness used in this phase of testing. In addition, other data included ventilation temperature, ventilation pressure, mass flow rate, nacelle free volume, extinguishant discharge time, and compartment surface temperature.

Type K thermocouples were used to measure the surface temperature of the compartment walls as well as the ventilation air temperatures.

3.1.7 Photo Coverage

Static photographic support was provided by the Aeronautical System Center (ASC) Technical Photo Department located at WPAFB.

3.1.8 Video

Video cameras were placed at two locations to view the fire through ports on the nacelle fixture. One view was from directly behind the fuel injection nozzle looking downstream. The other was a side view of the fire location. The two views of each fire test are recorded on videotape which becomes part of the permanent record of the program.

3.2 Procedure

3.2.1 Qualification Testing

The purpose of this phase of testing was to qualify the new full-annulus test fixture at the AEN. For the eight combinations of those variables that influence fire quality - mass flow, air temperature, and air pressure - it had to be demonstrated that sustained fires could be achieved, and also extinguished, under all the setting conditions required by the 32-run Phase I test matrix. The methodology of qualifying the operating parameters for this new test fixture followed the lessons learned from the previous year's testing with the 1/3-annulus test fixture. See Appendix A for test-peculiar information.

The Qualification Test Series consisted of four stages. Stage I was simply a system checkout of the fixture itself. Stage II established the values of the airflow parameters that the facility could support. Stage III was the actual flammability qualification test process that insured sustained fires would result at each combination of parameter settings used in the L-32 Phase I Parameter Study Test Matrix following the Qualification Testing. Stage IV explored different worst-case scenarios to insure that a maximum charge of extinguishant could extinguish a fire. It was important to establish the fact that not only could a reliable fire be maintained for each airflow associated with the various combinations of mass flow, air

temperature, and air pressure, but that a maximum charge of extinguishant (limited by the extinguisher size) would extinguish these fires.

3.2.1.1 Stage I - System Checkout

When the test engineers felt the primary installation and implementation task was complete, all critical instrumentation was in working order, all plumbing and hardware was attached, and all system components were operational, the qualification testing began. Prior to an actual test, the following checkouts were made:

1. Nitrogen pressurization checkout: It was demonstrated that for both the atmospheric and high pressure atmospheric conditions in the nacelle, the nitrogen pressure regulator system could be maintained at the 0.5 psia pressure differential within the inner nacelle core above the testing air pressure. This was required for heater operation to insure that hot flammable gases would not enter the inside of the engine core and be explosive. Even though this 0.5 psia pressure differential was manually operated (eventually an automatic system was installed), testing was allowed to proceed since the heater could adequately be protected.

2. Heater checkout: A graduated test series was conducted to allow for the heater components, and the surrounding material, to gradually be prepared for maximum thermal loads.

3.2.1.2 Stage II - Facility Extremes/Airflow Parameter Settings

The purpose of this phase of the qualification testing was to establish the maximum and minimum parameter levels for mass flow, air pressure, and air temperature the facility and the new test section could support. It was important to realize that due to the operation of the facility at extreme settings, these three parameters might be very dependent upon each other.

<u>Stage IIa: Prefire system testing</u>. The 24-inch inner core section was installed with 1-inch clutter (LOW). Using the high pressure air system and beginning with 0.1 lb/s mass flow, minimum and maximum attainable air pressure values were established. Mass flow was increased by 0.1 lb/s and again maximum attainable air pressure values were measured. Minimum mass flow required to maintain a maximum air pressure was recorded. Results are reported in Table 3-3. Mass flows below 0.5 lb/s did not permit stable air flows due to control relays. Therefore, Table 3-3 only indicates the results at and above 0.5 lb/s of mass flow.

Table 3-3. Mass Flow Versus Pressure

MASS FLOW (lb/s)	MAX PRESSURE SUPPORTED (psia)
0.1-0.49	unstable
0.5	15 stable
0.6	15.2
0.7	15.5
0.8	15.8
0.9	16.04
1.0	16.3
1.08	16.5
1.25	17.0

A similar, less extensive test of the blower system was done to investigate minimum pressures and mass flow values that could be obtained with the blower. For the range of mass flow rate and pressure extremes demonstrated (and necessary to maintain tangible extremes in testing), only 2.75 lb/s of airflow could be used to heat the air to 275° F and generate 17 psia of air. A minimum temperature of 100° F was used because it was controllable, being above ambient, since a chiller was not available to control the temperature at lower levels. As a result of these tests the settings shown below in Table 3-4 were set as extremes for the major air-related parameters used in experiments.

Table 3-4. Air-Related Parameter Settings

PARAMETER	LOW	HIGH
Mass flow	1.25 lb/s	2.75 lb/s
Air Pressure	14.5 psia	17 psia
Air Temperature	100° F	275° F

Stage IIb: Hot Surface Measurements. As a result of previous studies, a hot surface temperature of 1300° F was desired for the hot surface temperature HIGH setting. Testing was done and confirmed that this condition could be achieved.

3.2.1.3 Stage III - L-32 Qualification Testing - Flammability Studies

The purpose of this stage of testing was to establish that a strong 5 second fire was attainable at each of the airflows resulting from the various combinations of mass flow, air temperature, and air pressure. Testing incorporated both fuels (JP-8 and MIL-H-83282) at 100° F and used four different nozzles for each fuel. The full nacelle was in the TOP configuration with the 36-inch inner core section and 2-inch clutter (HIGH) installed. Parameter settings are summarized below in Table 3-5.

Table 3-5. Flammability Studies Parameter Settings

PARAMETER	SETTING
Clutter	2"
Fuel Temperature	100° F
Burn Time	5 sec
Fire Location	Top
Clearance	6 inches
Fuel	JP-8 & MIL-H-83282

The first exercise investigated the vertical positioning of the fuel nozzles. Following qualification tests to determine the thermocouple locations for flame temperature measurements, it was determined that two open-ended thermocouples would be installed so that the ends were 0.5-inch off the 36-inch core section surface. For consistency, the temperature, measured by a thermocouple located 6 inches downstream, would be used for the evaluation. Using this process, it was found that the vertical positions of 0.5 or 0.75-inch above the core section caused

the hottest flame temperatures. Lower temperatures were observed if the nozzle was placed any closer to the core surface, and in some cases a fire was not possible.

After the thermocouple and nozzle vertical positions were established, the flammability study was begun. Initially, it was desired that the total 64 configuration matrix would be run twice using two different longitudinal locations for the igniter. This would accommodate off-stoichiometric combustion conditions and insure that all extinguishants were tested against a fully developed hot fire. However, scheduling constraints forced the selection and utilization of only one igniter location.

Table 3-6 shows the results of the flammability study. Each nozzle (FNOZ) and fuel type category is grouped for easy comparison. For MIL-H-83282 hydraulic fluid, the 2 and 6 gallons/hour (gph) rated nozzles were ruled out because there were cases where a flame could not be lit. Based on the highest average temperatures observed, the 6 gph rated nozzle was selected for JP-8 and the 4 gph rated nozzle was selected for MIL-H-83282. Accordingly, for the rest of the qualification testing, and for the Phase I Parameter Study Test Matrix, these nozzles were used with their respective fuels. The actual fuel mass flows as determined from collected discharges for the nozzles were: JP-8, with a 6 gph rated Monarch Nozzle - 11.3 gph; and, MIL-H-83282, with a 4 gph rated Stainless Nozzle - 33.91 gph. These higher flow rates were due to the high pressures applied to the systems.

3.2.1.4 Stage IV - L-32 Qualification Testing - Fire Suppression Studies

The purpose of this stage of the Qualification Test Series was to verify that all fires could be suppressed by a maximum volume of extinguishant. These tests brought to light the issue of reignition. This phenomenon required that a new parameter — post-discharge fuel flow time (PTIM) — be established for each of the two fuels used. Post-discharge fuel flow time was defined to be the maximum length of time the fuel could continue to flow after the initial release of the maximum amount of extinguishant available and not have a reignition. The parameter settings used in this testing, which were considered to be worst-case fires, are presented in Table 3-7.

Table 3-8 summarizes the results of this testing. The first test confirmed the possibility that a maximum amount of extinguishant would not be able to extinguish a fire. Perfluorohexane was not able to extinguish a fire when the Extinguishant Discharge Location was SIDE, Configuration SHORT, and Fire Location TOP. Subsequent tests with Halon 1301, HFC-227ea, HFC-125, and CF_3I showed that maximum fills of these extinguishants were able to extinguish the fire with these parameter settings. As a result, perfluorohexane was dropped from the program, and HFC-227ea was inserted as the second extinguishant to be used with Halon 1301 since it differed most dramatically from halon among the remaining effective extinguishants. This replacement applied to the Phase I Parameter Study Test Matrix as well as in the rest of the Qualification Test Series. Table 3-8 also shows that there were no reignitions for either a TUBE or DUMP release of maximum extinguishant quantity at 5 seconds or less of post-discharge fuel flow time for any extinguishant. The TUBE test of CF_3I was never conducted because of bad weather restrictions on when CF_3I could be tested. The first eight tests used a post-discharge fuel flow time (PTIM) of 3 seconds.

Table 3-6. Flammability Study Test Matrix

TEST	INTE (lb/s)	APRS (psia)	ATMP (° F)	FUEL	FNOZ (gph)	FTMP (° F)
1	1.25	14.5	100	JP-8	2	978
2	1.25	14.5	100	JP-8	4	1148
3	1.25	14.5	100	JP-8	6	1383
4	1.25	14.5	100	JP-8	8	1315
5	1.25	14.5	100	83282	2	1900
6	1.25	14.5	100	83282	4	1760
7	1.25	14.5	100	83282	6	1777
8	1.25	14.5	100	83282	8	1422
9	1.25	14.5	275	JP-8	2	1103
10	1.25	14.5	275	JP-8	4	1328
11	1.25	14.5	275	JP-8	6	1281
12	1.25	14.5	275	JP-8	8	1349
13	1.25	14.5	275	83282	2	1716
14	1.25	14.5	275	83282	4	1834
15	1.25	14.5	275	83282	6	1669
16	1.25	14.5	275	83282	8	
17	1.25	17.0	100	JP-8	2	926
18	1.25	17.0	100	JP-8	4	1150
19	1.25	17.0	100	JP-8	6	1296
20	1.25	17.0	100	JP-8	8	1243
21	1.25	17.0	100	83282	2	1896
22	1.25	17.0	100	83282	4	1911
23	1.25	17.0	100	83282	6	NONE
24	1.25	17.0	100	83282	8	871
25	1.25	17.0	275	JP-8	2	1013
26	1.25	17.0	275	JP-8	4	1049
27	1.25	17.0	275	JP-8	6	1312
28	1.25	17.0	275	JP-8	8	1131
29	1.25	17.0	275	83282	2	1772
30	1.25	17.0	275	83282	4	1806
31	1.25	17.0	275	83282	6	357
32	1.25	17.0	275	83282	8	830

TEST	INTE (lb/s)	APRS (psia)	ATMP (° F)	FUEL	FNOZ (gph)	FTMP (° F)
33	3.00	14.5	100	JP-8	2	1083
34	3.00	14.5	100	JP-8	4	1132
35	3.00	14.5	100	JP-8	6	1511
36	3.00	14.5	100	JP-8	8	1328
37	3.00	14.5	100	83282	2	NONE
38	3.00	14.5	100	83282	4	1807
39	3.00	14.5	100	83282	6	1851
40	3.00	14.5	100	83282	8	1963
41	3.00	14.5	275	JP-8	2	1238
42	3.00	14.5	275	JP-8	4	1322
43	3.00	14.5	275	JP-8	6	1381
44	3.00	14.5	275	JP-8	8	1316
45	3.00	14.5	275	83282	2	1748
46	3.00	14.5	275	83282	4	1966
47	3.00	14.5	275	83282	6	1747
48	3.00	14.5	275	83282	8	2000
49	3.00	17.0	100	JP-8	2	1200
50	3.00	17.0	100	JP-8	4	1282
51	3.00	17.0	100	JP-8	6	1396
52	3.00	17.0	100	JP-8	8	1177
53	3.00	17.0	100	83282	2	NONE
54	3.00	17.0	100	83282	4	1641
55	3.00	17.0	100	83282	6	1611
56	3.00	17.0	100	83282	8	1532
57	3.00	17.0	275	JP-8	2	1228
58	3.00	17.0	275	JP-8	4	1246
59	3.00	17.0	275	JP-8	6	1339
60	3.00	17.0	275	JP-8	8	1334
61	3.00	17.0	275	83282	2	1295
62	3.00	17.0	275	83282	4	1909
63	3.00	17.0	275	83282	6	625
64	3.00	17.0	275	83282	8	1941

Table 3-7. Post-Discharge Fuel Flow Time Study - Parameter Settings

PARAMETER	SETTING
Extinguishant	All
Extinguishant Amount	Max
Extinguishant Discharge Location	Side
Extinguishant Pressure	400 psia
Extinguishant Temperature	-20° F
Air Pressure	17 psia
Air Temperature	275° F
Clutter	2"
Configuration	Short
Clearance	6 inches
Distribution	Dump, Tube
Fire Location	Top
Fuel	JP-8, MIL-H-83282
Hot Surface	1300° F
Mass Flow	2.75 lb/s
Preburn Time	20 sec

Table 3-8. Post-Discharge Fuel Flow Time Study Results - JP-8

RUN	DIST	EXTNGT	PTIM (sec)	AMT (lbs)**	REIG?
1	Dump	Perfluorohexane	3	32.5	Y*
2	Dump	1301	3	32.5	N
3	Dump	HFC-227ea	3	28.5	N
4	Dump	HFC-125	3	24.5	N
5	Dump	CF_3I	3	32.5	N
6	Tube	HFC-227ea	3	28.5	N
7	Tube	HFC-125	3	24.5	N
8	Dump	CF_3I	3	10.0	N
9	Dump	HFC-227ea	6	28.5	Y
10	Dump	HFC-227ea	4.5	28.5	N
11	Dump	HFC-227ea	5.3	28.5	N
12	Dump	CF_3I	5.3	24.5	N
13	Dump	HFC-125	5.3	24.5	N

*Fire could not be extinguished using Perfluorohexane.
**Maximum amount of extinguishant stored (variable due to density) -Test #8 was an exception.

Once it was established that fires could be extinguished, the next step was to vary the post-discharge fuel flow time itself. This was done using the same conditions outlined above with HFC-227ea as the extinguishant. Table 3-8 shows that with a post-discharge time of 5.3 seconds there was no hot surface reignition, but with a post-discharge of 6 seconds there was. Additional tests with maximum allowable fills of HFC-125 and CF_3I confirmed that there was no hot surface reignition with the 5.3 second post-discharge. As a result, it was established that for JP-8, a post-discharge fuel flow time of 5 seconds would be used for Phase I testing.

Further testing using MIL-H-83282 hydraulic fluid uncovered a worse situation. Hydraulic fluid burns in a very rich manner, i.e., there is excess hydraulic fluid that does not burn. Consequently, hydraulic fluid revealed a greater tendency for hot surface reignition. The fluid that does not burn is blown downstream along the core section outer surface, until it comes in contact with the hot surface. Sometimes this reignition process took 15 to 17 seconds after the extinguisher was fired. Table 3-9 shows the results of a short test series which varied the post-discharge fuel flow time of the MIL-H-83282 to study this situation. In order to obtain a condition where maximum amounts of extinguishant could prevent a hot surface ignition, the post-discharge fuel flow time had to be set to 0 seconds.

Table 3-9. Post-Discharge Fuel Flow Time Study Results - MIL-H-83282

RUN	DIST	EXTNGT	PTIM (sec)	AMT (lbs)	REIG?
1	Dump	HFC-227ea	5	28.50	Y
2	Dump	HFC-227ea	2.5	28.50	Y
3	Dump	HFC-227ea	1.3	28.50	Y
4	Dump	HFC-227ea	0	28.50	Y
5	Dump	CF_3I	0	10.00	N

Additional testing was conducted to ensure that maximum amounts of each of the three candidate extinguishants (HFC-227ea, HFC-125, and CF_3I) would extinguish a worst-case fire using both distribution methods (TUBE and DUMP) with the fire on the opposite side (BOTTOM) of the nacelle from the extinguishant discharge location (TOP). Table 3-10 shows the settings which were used for this test series. Table 3-11 shows the results; in all six test runs, the fire was extinguished with no reignition.

Table 3-10. Worst-Case Fire Parameter Settings

PARAMETER	SETTING	PARAMETER	SETTING
Air Pressure	17 psia	Extinguishant Temperature	-20° F
Air Temperature	275° F	Extinguishant Pressure	400 psia
Mass Flow	2.75 lb/s	Fire Location	Bottom
Preburn Time	20 seconds	Configuration	Short
Extinguishant Discharge Location	Top	Clearance	6 inches
Post-Discharge Time	5 seconds	Clutter	2"
Fuel	JP-8	Hot Surface	Off
Extinguishant	HFC 227ea, HFC 125, CF_3I	Extinguishant Distribution	Tube, Dump
Extinguishant Amount	Max	Fuel Temperature	100° F

Table 3-11. Worst-Case Fire Results

RUN	DISTRIBUTION	EXTINGUISHANT	AMOUNT (lbs)	FIRE EXTINGUISHED
4a1a	Dump	HFC-227ea	28.5	YES
4a1b	Tube	HFC-227ea	28.5	YES
4a2a	Dump	HFC-125	24.5	YES
4a2b	Tube	HFC-125	24.5	YES
4a3a	Dump	CF_3I	10.0	YES
4a3b	Tube	CF_3I	10.0	YES

Reignition after the extinguishant has been dumped is an issue if fuel continues to flow and an ignition source is still available (such as the simulated hot engine casing). This methodology of setting the post-discharge fuel flow time to a value where the maximum amount of available extinguishant will prevent a reignition has been selected as the standard for this program. The maximum available extinguishant was limited by the extinguisher size. It was sized by determining the maximum amount of halon stored per unit volume that is currently fielded in existing aircraft and adjusted for the volume of the existing simulator. In essence, it is sized to deliver the maximum amount of halon available in existing systems, with a corresponding overall level of protection and range of protection conditions equivalent to existing systems. This quantity was calculated to be approximately 32 pounds of halon and the test extinguisher was sized to this amount. Due to density variations, slightly different mass maximums of the alternative extinguishants are possible. The reignition phenomenon is a significant problem and should be studied in further testing. Resource constraints did not allow any further investigation under this test program.

3.2.2 Full-Scale Testing

Data collection worksheets for the basic 32-run test matrix design were provided to test personnel. This experimental configuration was developed using a Placket-Burman experimental matrix to determine the relative influence of each of these variables on the response variable, or output, which is the amount of extinguishant required to extinguish a particular fire. Table 3-12 shows these worksheets. This worksheet records the LOW/HIGH level settings for each factor for each test run. Run 1 shows each factor set at its LOW level. Successive test runs vary the level of different factors as shown.

Each test run was repeated four times (adjusting the extinguishant quantity using the bracketing procedure) and an estimate of the amount of extinguishant required to extinguish the fire obtained. This procedure was required because of the difficulty involved in directly determining the response variable as previously described in Paragraph 3.0. The bracketing procedure is shown in Figure 3-1.

Table 3-12. Data Collection Worksheet

RUN	CLEAR (in)	CONF	INTE (lb/s)	LOCA	CLUT	STMP (° F)	DIST	BTMP	PREB (sec)	BPRS (psia)	APRS (psia)	EXTNGT	ATMP (° F)	FUEL	FTMP (° F)	ALOC	AMT (lbs)
1	6	Short	1.25	Bot	Low	175	Dump	Low	5	400	14.5	HFC-227ea	100	83282	100	Side	
2	6	Short	1.25	Bot	Low	175	Dump	Low	20	800	17	1301	275	JP-8	325	Top	
3	6	Short	1.25	Bot	High	1300	Tube	High	20	800	17	1301	100	83282	100	Side	
4	6	Short	1.25	Bot	High	1300	Tube	High	5	400	14.5	HFC-227ea	275	JP-8	325	Top	
5	6	Short	2.75	Top	High	1300	Dump	Low	5	400	17	1301	275	JP-8	100	Side	
6	6	Short	2.75	Top	High	1300	Dump	Low	20	800	14.5	HFC-227ea	100	83282	200	Top	
7	6	Short	2.75	Top	Low	175	Tube	High	20	800	14.5	HFC-227ea	275	JP-8	100	Side	
8	6	Short	2.75	Top	Low	175	Tube	High	5	400	17	1301	100	83282	200	Top	
9	6	Long	2.75	Bot	Low	1300	Tube	Low	5	800	17	HFC-227ea	100	JP-8	325	Side	
10	6	Long	2.75	Bot	Low	1300	Tube	Low	20	400	14.5	1301	275	83282	100	Top	
11	6	Long	2.75	Bot	High	175	Dump	High	20	400	14.5	1301	100	JP-8	325	Side	
12	6	Long	2.75	Bot	High	175	Dump	High	5	800	17	HFC-227ea	275	83282	100	Top	
13	6	Long	1.25	Top	High	175	Tube	Low	5	800	14.5	1301	275	83282	200	Side	
14	6	Long	1.25	Top	High	175	Tube	Low	20	400	17	HFC-227ea	100	JP-8	100	Top	
15	6	Long	1.25	Top	Low	1300	Dump	High	20	400	17	HFC-227ea	275	83282	200	Side	
16	12	Long	1.25	Top	Low	1300	Dump	High	5	800	14.5	1301	100	JP-8	100	Top	
17	12	Long	1.25	Bot	Low	175	Tube	High	5	400	17	1301	275	JP-8	100	Side	
18	12	Long	1.25	Bot	Low	175	Tube	High	20	800	14.5	HFC-227ea	100	83282	200	Top	
19	12	Long	1.25	Bot	High	1300	Dump	Low	20	800	14.5	HFC-227ea	275	JP-8	100	Side	
20	12	Long	1.25	Bot	High	1300	Dump	Low	5	400	17	1301	100	83282	200	Top	
21	12	Long	2.75	Top	High	1300	Tube	High	5	400	14.5	HFC-227ea	100	83282	100	Side	
22	12	Long	2.75	Top	High	1300	Tube	High	20	800	17	1301	275	JP-8	325	Top	
23	12	Long	2.75	Top	Low	175	Dump	Low	20	800	17	1301	100	83282	100	Side	
24	12	Long	2.75	Top	Low	175	Dump	Low	5	400	14.5	HFC-227ea	275	JP-8	325	Top	
25	12	Short	2.75	Bot	Low	1300	Dump	High	5	800	14.5	1301	275	83282	200	Side	
26	12	Short	2.75	Bot	Low	1300	Dump	High	20	400	17	HFC-227ea	100	JP-8	100	Top	
27	12	Short	2.75	Bot	High	175	Tube	Low	20	400	17	HFC-227ea	275	83282	200	Side	
28	12	Short	2.75	Bot	High	175	Tube	Low	5	800	14.5	1301	100	JP-8	100	Top	
29	12	Short	1.25	Top	High	175	Dump	High	5	800	17	HFC-227ea	100	JP-8	325	Side	
30	12	Short	1.25	Top	High	175	Dump	High	20	400	14.5	1301	275	83282	100	Top	
31	12	Short	1.25	Top	Low	1300	Tube	Low	20	400	14.5	1301	100	JP-8	High	Side	
32	12	Short	1.25	Top	Low	1300	Tube	Low	5	800	17	HFC-227ea	275	8328	Low	Top	

The procedures which were followed in the conduct of Phase I testing are presented below.

1. Configure test article.
2. Charge extinguishant distribution bottle.
3. Physically leave room if fire test involved.
4. Set remaining test parameters.
5. Initiate data acquisition instrumentation.
6. Initiate test fire.
7. Release extinguishant after predetermined preburn time.
8. Continue fuel flow for 5 seconds after extinguishant release to insure fuel reaches engine (0 seconds for MIL-H-83282).
9. Terminate data acquisition after 45 seconds.
10. Continue, or increase, airflow to cool down test article (560°R).
11. Remove fuel from facility.
12. Shut down to prepare for next test.

A TI Programmer or equivalent was used for all critical timing events. Output response variables recorded were:

1. Amount of extinguishant used to extinguish the fire.
2. Fire intensity (thermocouple, TV).
3. Temperature of exhaust gases.
4. CO and CO_2 in exhaust gases.
5. Time to extinguish fire (extinguishant dump to fire out).
6. Keep down time - fire out to reignition - if reignition occurred.

The following sequence of pictures and diagrams illustrates a test configuration and results. Figures 3-5 through 3-8 show the engine nacelle fire with fuel spray and the nacelle fire after the fuel spray was turned off.

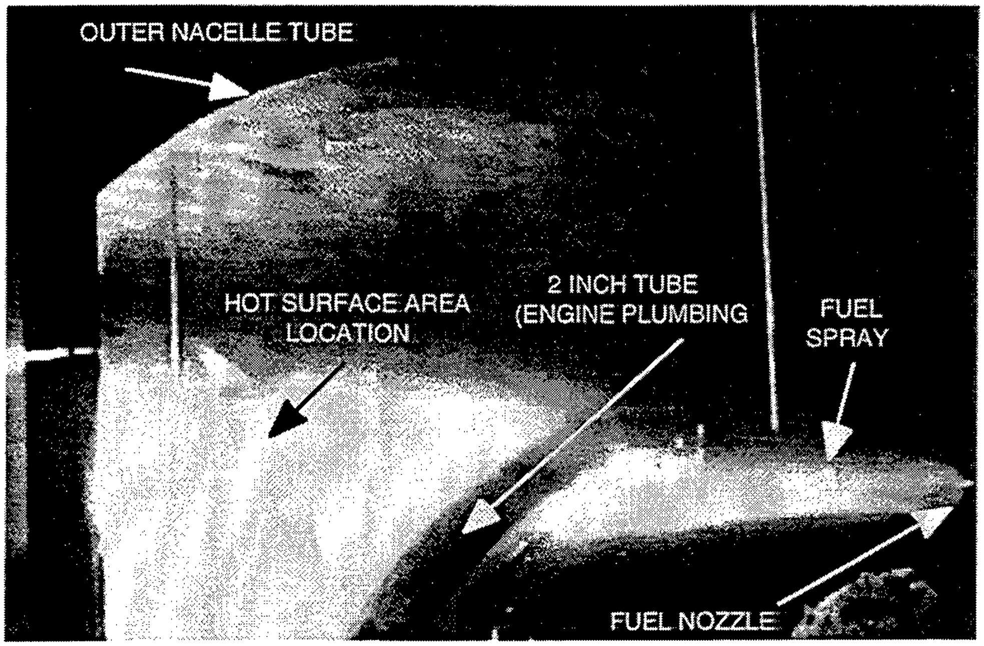

Figure 3-5. Picture of Engine Nacelle Fire With Fuel Spray

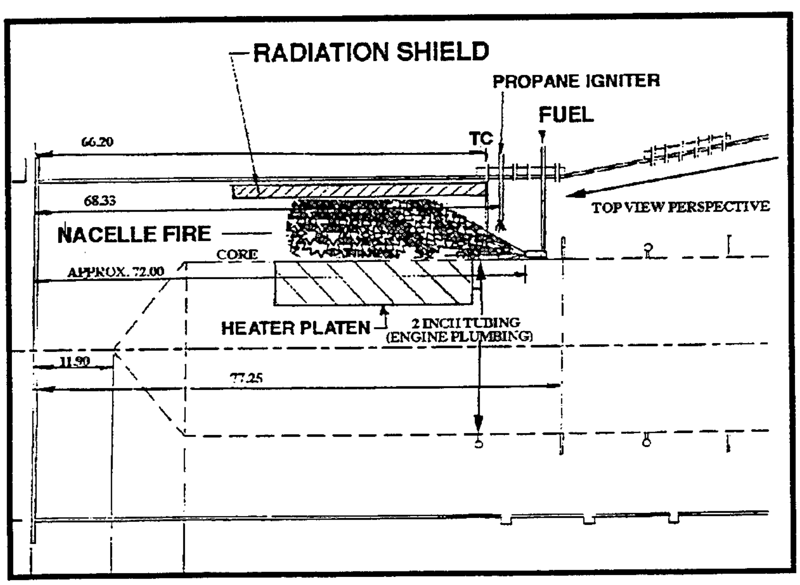

Figure 3-6. Diagram of Engine Nacelle Fire With Fuel Spray

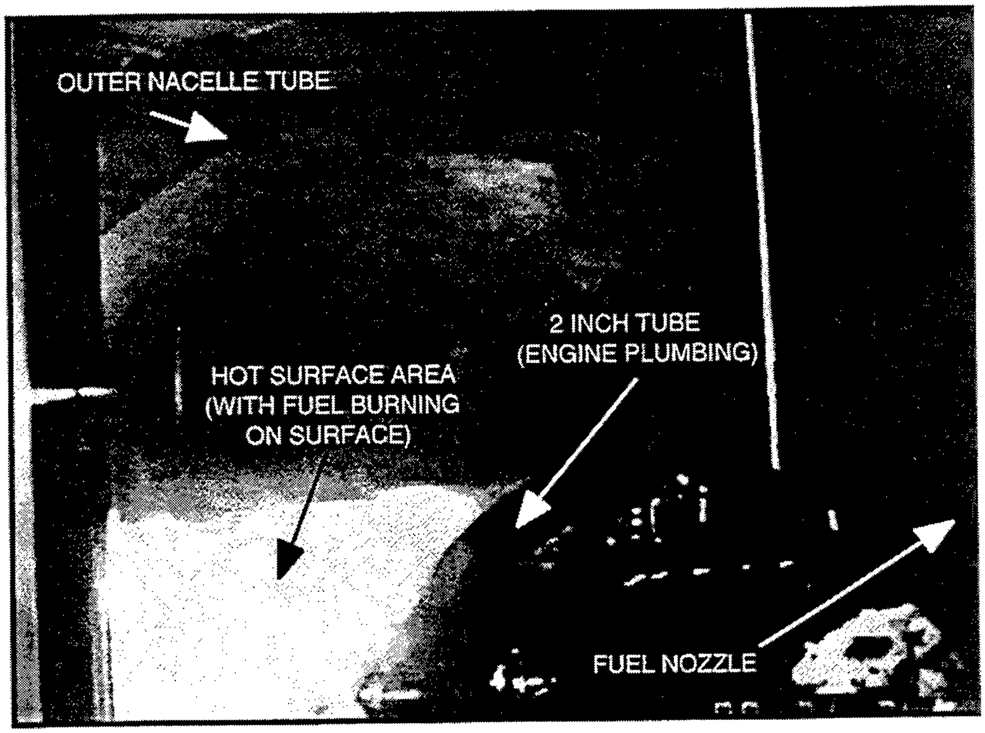

Figure 3-7. Picture of Engine Nacelle Fire With Fuel Spray Turned Off

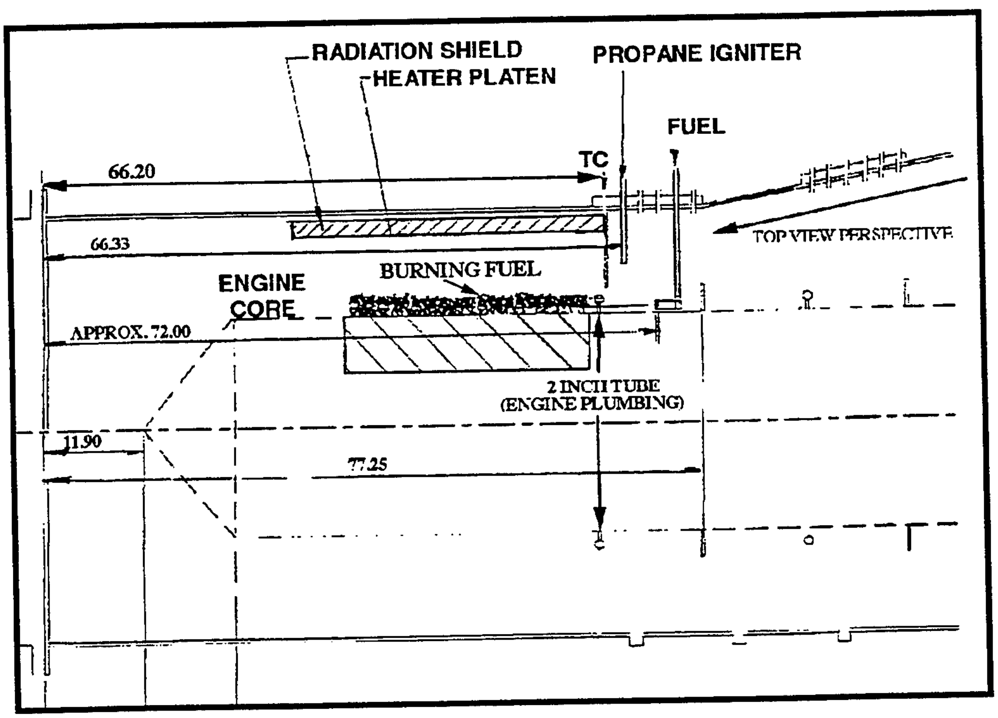

Figure 3-8. Diagram of Engine Nacelle Fire With Fuel Spray Turned Off

4.0 RESULTS

4.1 Data Analysis

The factors used in Phase I and the settings for each level are shown in Table 4-1. The 32-run Phase I Test Matrix and the factor settings, shown as -1 and 1 for the Low and High Settings, respectively, are shown in Table 4-2. The 32-run Phase I Test Matrix with the actual factor settings and the value of the response variable are shown in Table 4-3. The response variable (AMT) is defined to be the average of the minimum weight of extinguishant that put out the fire and the maximum weight of extinguishant that did not, and was determined using the bracketing procedure described previously.

Table 4-1. Phase I Parameters and Settings

PARAMETER	SYMBOL	LOW SETTING (-1)	HIGH SETTING (+1)
Extinguishant	EXTNGT	HFC-227ea	Halon 1301
Extinguishant Discharge Location	ALOC	Side	Top
Extinguishant Distribution	DIST	Dump	Tube
Extinguishant Temperature	BTMP	-20° F	160° F
Air Pressure	APRS	14.5 psia	17.0 psia
Air Temperature	ATMP	100° F	275° F
Bottle Pressure	BPRS	400 psi	800 psi
Clutter	CLUT	Low (1-inch)	High (2 inches)
Configuration	CONF	Short	Long
Clearance	CLEAR	6 inches	12 inches
Fire Location	LOCA	Bottom	Top
Fuel	FUEL	MIL-H-83282	JP-8
Fuel Temperature	FTMP	100° F	200° F(83282) 325° F(JP-8)
Internal Air Flow	INTE	1.25 lb/s	2.75 lb/s
Preburn Time	PREB	5 sec	20 sec
Surface Temperature	STMP	175° F	1300° F

Table 4-2. Phase I Test Matrix Showing Orthogonal High-Low Pattern

CLEAR	CONF	INTE	LOCA	CLUT	STMP	DIST	BTMP	PREB	BPRS	APRS	EXTGT	ATMP	FUEL	FTMP	ALOC
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1
-1	-1	-1	-1	1	1	1	1	1	1	1	1	-1	-1	-1	-1
-1	-1	-1	-1	1	1	1	1	-1	-1	-1	-1	1	1	1	1
-1	-1	1	1	1	1	-1	-1	-1	-1	1	1	1	1	-1	-1
-1	-1	1	1	1	1	-1	-1	1	1	-1	-1	-1	-1	1	1
-1	-1	1	1	-1	-1	1	1	1	1	-1	-1	1	1	-1	-1
-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1
-1	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1
-1	1	1	-1	-1	1	1	-1	1	-1	-1	1	1	-1	-1	1
-1	1	1	-1	1	-1	-1	1	1	-1	-1	1	-1	1	1	-1
-1	1	1	-1	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1
-1	1	-1	1	1	-1	1	-1	-1	1	-1	1	1	-1	1	-1
-1	1	-1	1	1	-1	1	-1	1	-1	1	-1	-1	1	-1	1
-1	1	-1	1	-1	1	-1	1	1	-1	1	-1	1	-1	1	-1
-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1
1	1	-1	-1	-1	-1	1	1	-1	-1	1	1	1	1	-1	-1
1	1	-1	-1	-1	-1	1	1	1	1	-1	-1	-1	-1	1	1
1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1
1	1	-1	-1	1	1	-1	-1	-1	-1	1	1	-1	-1	1	1
1	1	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	-1	-1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	-1	-1	-1	-1	1	1	1	1	-1	-1	-1	-1
1	1	1	1	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1
1	-1	1	-1	-1	1	-1	1	-1	1	-1	1	1	-1	1	-1
1	-1	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1
1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1
1	-1	1	-1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1
1	-1	-1	1	1	-1	-1	1	-1	1	1	-1	-1	1	1	-1
1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1
1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1	1	-1
1	-1	-1	1	-1	1	1	-1	-1	1	1	-1	1	-1	-1	1

Table 4-3. Phase I Test Matrix With Response Variable

RUN	CLEAR (in)	CONF	INTE (lb/s)	LOCA	CLUT	STMP (° F)	DIST	BTMP (° F)	PREB (sec)	BPRS (psia)	APRS (psia)	EXTNGT	ATMP (° F)	FUEL	FTMP (° F)	ALOC.	AMT (lbs)
1	6	Short	1.25	Bot	Low	175	Dump	-20	5	400	14.5	HFC-227ea	100	83282	100	Side	1.375
2	6	Short	1.25	Bot	Low	175	Dump	-20	20	800	17	1301	275	JP-8	325	Top	1.125
3	6	Short	1.25	Bot	High	1300	Tube	160	20	800	17	1301	100	83282	100	Side	2.750
4	6	Short	1.25	Bot	High	1300	Tube	160	5	400	14.5	HFC-227ea	275	JP-8	325	Top	9.000
5	6	Short	2.75	Top	High	1300	Dump	-20	5	400	17	1301	275	JP-8	100	Side	1.375
6	6	Short	2.75	Top	High	1300	Dump	-20	20	800	14.5	HFC-227ea	100	83282	200	Top	17.57
7	6	Short	2.75	Top	Low	175	Tube	160	20	800	14.5	HFC-227ea	275	JP-8	100	Side	0.940
8	6	Short	2.75	Top	Low	175	Tube	160	5	400	17	1301	100	83282	200	Top	0.141
9	6	Long	2.75	Bot	Low	1300	Tube	-20	5	800	17	HFC-227ea	100	JP-8	325	Side	1.875
10	6	Long	2.75	Bot	Low	1300	Tube	-20	20	400	14.5	1301	275	83282	100	Top	6.875
11	6	Long	2.75	Bot	High	175	Dump	160	20	400	14.5	1301	100	JP-8	325	Side	0.345
12	6	Long	2.75	Bot	High	175	Dump	160	5	800	17	HFC-227ea	275	83282	100	Top	3.750
13	6	Long	1.25	Top	High	175	Tube	-20	5	800	14.5	1301	275	83282	200	Side	0.235
14	6	Long	1.25	Top	High	175	Tube	-20	20	400	17	HFC-227ea	100	JP-8	100	Top	2.250
15	6	Long	1.25	Top	Low	1300	Dump	160	20	400	17	HFC-227ea	275	83282	200	Side	26.94
16	6	Long	1.25	Top	Low	1300	Dump	160	5	800	14.5	1301	100	JP-8	100	Top	0.815
17	12	Long	1.25	Bot	Low	175	Tube	160	5	400	17	1301	275	JP-8	100	Side	4.500
18	12	Long	1.25	Bot	Low	175	Tube	160	20	800	14.5	HFC-227ea	100	83282	200	Top	3.250
19	12	Long	1.25	Bot	High	1300	Dump	-20	20	800	14.5	HFC-227ea	275	JP-8	100	Side	4.500
20	12	Long	1.25	Bot	High	1300	Dump	-20	5	400	17	1301	100	83282	200	Top	9.000
21	12	Long	2.75	Top	High	1300	Tube	160	5	400	14.5	HFC-227ea	100	83282	100	Side	9.000
22	12	Long	2.75	Top	High	1300	Tube	160	20	800	17	1301	275	JP-8	325	Top	15.00
23	12	Long	2.75	Top	Low	175	Dump	-20	20	800	17	1301	100	83282	100	Side	0.940
24	12	Long	2.75	Top	Low	175	Dump	-20	5	400	14.5	HFC-227ea	275	JP-8	325	Top	5.500
25	12	Short	2.75	Bot	Low	1300	Dump	160	5	800	14.5	1301	275	83282	200	Side	15.00
26	12	Short	2.75	Bot	Low	1300	Dump	160	20	400	17	HFC-227ea	100	JP-8	100	Top	10.50
27	12	Short	2.75	Bot	High	175	Tube	-20	20	400	17	HFC-227ea	275	83282	200	Side	17.57
28	12	Short	2.75	Bot	High	175	Tube	-20	5	800	14.5	1301	100	JP-8	100	Top	1.125
29	12	Short	1.25	Top	High	175	Dump	160	5	800	17	HFC-227ea	100	JP-8	325	Side	2.250
30	12	Short	1.25	Top	High	175	Dump	160	20	400	14.5	1301	275	83282	100	Top	0.280
31	12	Short	1.25	Top	Low	1300	Tube	-20	20	400	14.5	1301	100	JP-8	High	Side	15.00
32	12	Short	1.25	Top	Low	1300	Tube	-20	5	800	17	HFC-227ea	275	8328	Low	Top	7.500

4.1.1 Analysis of the Factorial Experiment

The calculations of effect size and sum of squares for each factor and interaction sets between factors were performed and the results are shown in Table 4-4. The sum of squares for each factor was then expressed as a percent of total variability. The larger the percentage of total variability accounted for by any factor, the stronger the indication from the data that the effect of that factor on the response variable is of sufficient size to stand out from the experimental error, or "noise."

Table 4-4. Analysis of the Factorial Experiment

FACTOR	EFFECT	SUM OF SQUARES	PERCENT OF TOTAL
STMP	6.69525	358.611	26.1423
FTMP	5.08225	206.634	15.0634
IA Set 5	3.38713	91.7809	6.69073
PREB	3.3365	89.0579	6.49222
IA Set 13	3.17588	80.6895	5.88217
EXTNGT	-3.07838	75.8111	5.52655
FUEL	-2.87913	66.3149	4.83428
CLEAR	2.72213	59.2797	4.32142
ATMP	2.619	54.8733	4.0002
BPRS	-2.56412	52.5979	3.83433
IA Set 9	2.49837	49.935	3.64021
IA Set 14	2.35913	44.5238	3.24573
IA Set 8	-2.071	34.3123	2.50133
IA Set 12	-1.6915	22.8894	1.66861
IA Set 10	-1.6465	21.6877	1.58101
IA Set 3	-1.39288	15.5208	1.13145
INTE	1.04537	8.74247	0.637316
APRS	1.041	8.66945	0.631993
IA Set 15	-0.83475	5.57446	0.406372
LOCA	0.82475	5.4417	0.396694
ALOC	-0.682125	3.72236	0.271356
BTMP	0.666	3.54845	0.258678
IA Set 1	0.659	3.47425	0.253269
CONF	-0.54475	2.37402	0.173063
IA Set 4	0.44525	1.58598	0.115616
IA Set 6	-0.434	1.50685	0.109848
CLUT	-0.392875	1.23481	0.090016
IA Set 2	-0.2715	0.589698	0.0429883
DIST	-0.265875	0.565516	0.0412255
IA Set 11	-0.158375	0.200661	0.014628
IA Set 7	-0.040875	0.0133661	0.000974375
TOTAL		1371.763	100.00%

Those factors that were 3% or more of the total sum of squares were identified as variables to be included in the next phase of the experimentation. More typically, only those factors that are 5 to 10% of the total sum of squares would be identified as probably having an effect distinguishable from statistical noise. Since this was only the first phase of experimentation, it was decided to err on the conservative side and not exclude variables from future phases of the experiment.

Those factors that are each 3% or more of the total Sum of Squares are:

1. Surface Temperature (STMP) - 26.1%
2. Fuel Temperature (FTMP) - 15.1%
3. Preburn Time (PREB) - 6.5%
4. Extinguishant (EXTNGT) - 5.5%
5. Fuel (FUEL) - 4.8%
6. Clearance (CLEAR) - 4.3%
7. Air Temperature (ATMP) - 4.0%
8. Bottle Pressure (BPRS) - 3.8%
9. Two-factor interactions. The significant interaction (IA) sets are:

- IA Set 5 - 6.7%
- IA Set 13 - 5.9%
- IA Set 9 - 3.6%
- IA Set 14 - 3.2%

Each interaction set consists of eight two-factor interactions statistically confounded with one another. Determining which interactions in a given IA set are physically meaningful involves a combination of statistical analysis and engineering judgment. The statistical methodology is presented below.

The factors involved in each IA set are provided in Table 4-5.

Table 4-5. Confounded Two-factor Interaction Sets - Engine Nacelle

INTERACTION SETS	INTERACTIONS
IA Set 1	AB=CF=GH=EL=DK=MN=JO=IP
IA Set 2	AC=DG=BF=HK=IO=EM=LN=JP
IA Set 3	AD=CG=FH=IL=BK=JM=NO=EP
IA Set 4	AE=GJ=IK=BL=CM=FN=HO=DP
IA Set 5	BC=AF=DH=IJ=GK=LM=EN=OP
IA Set 6	BD=CH=EI=FG=AK=JN=MO=LP
IA Set 7	BE=DI=HJ=AL=FM=CN=GO=KP
IA Set 8	CD=AG=BH=EJ=FK=IN=LO=MP
IA Set 9	CE=DJ=HI=BN=FL=AM=KO=GP
IA Set 10	DE=BI=CJ=KL=GM=HN=FO=AP
IA Set 11	DF=BG=AH=CK=JL=IM=EO=NP
IA Set 12	EF=GI=JK=CL=BM=AN=DO=HP
IA Set 13	AI=EK=FJ=DL=HM=GN=CO=BP
IA Set 14	AJ=EG=FI=HL=DM=KN=BO=CP
IA Set 15	CI=BJ=EH=GL=KM=DN=AO=FP

FACTORS			
A=FTMP	E=CLEAR	I=STMP	M=ATMP
B=CLUT	F=PREB	J=LOCA	N=DIST
C=INTE	G=FUEL	K=EXTNGT	0=BRPS
D=CONF	H=BTMP	L=APRS	P=ALOC

To begin the statistical analysis, each of the factors (variables) was ranked from 16 (largest effect) to 1 (smallest effect) based on each factor's percent of total sum of squares (see Table 4-4). The ranking of the factors is given in Table 4-6.

Table 4-6. Rankings of Main Effects - Engine Nacelle

RANK NUMBER	FACTOR	RANK NUMBER	FACTOR	RANK NUMBER	FACTOR	RANK NUMBER	FACTOR
16	I	12	G	8	C	4	H
15	A	11	E	7	L	3	D
14	F	10	M	6	J	2	B
13	K	9	O	5	P	1	N

Next, each factor in an interaction was replaced by its rank number. The interaction (IA) between factors STMP and FTMP, for example, would be replaced by 16*15, indicating that this interaction involves the two largest main effects. Those interactions with the largest product would be likely candidates to be the interactions that are the active ones. It is possible for two factors to have small main effects but still have a significant interaction. This means the combination of settings of two or more variables have a pronounced effect on the response variable. However, typically one of the interaction factors is significant as a main effect by itself to produce a significant two-factor interaction with another. The interaction groups are shown in Table 4-7.

Table 4-7. Interaction Groups - Engine Nacelle

INTERACTION SET	INTERACTION PAIR WITH FACTOR REPLACED WITH RANK NUMBER IN THE ANALYSIS	MOST LIKELY INTERACTION COMBINATIONS
1	15*2=8*14=12*4=11*7=3*13=10*1=6*9=16*5	CF IP
2	15*8=3*12=2*14=4*13=16*9=11*10=7*1=6*5	AC IO
3	15*3=8*12=14*4=16*7=2*13=6*10=1*9=11*6	CG IL
4	15*11=12*6=16*13=2*7=8*10=14*1=4*9=3*5	AE IK
5	2*8=15*14=3*4=16*6=12*13=7*10=11*1=9*5	AF GK
6	2*3=8*4=11*16=14*12=15*13=6*1=10*9=7*6	EI AK
7	2*11=3*16=4*6=15*7=14*10=8*1=12*9=13*5	FM GO
8	8*3=15*12=2*4=11*6=14*13=16*1=7*9=10*5	AG FK
9	8*11=3*6=4*16=2*1=14*7=15*10=13*9=12*5	AM KO
10	3*11=2*16=8*6=13*7=12*10=4*1=14*9=15*5	GM FO
11	3*14=2*12=15*4=8*13=6*7=16*10=11*9=1*6	CK IM
12	11*14=12*16=6*13=8*7=2*6=15*1=3*9=4*5	EF GI
13	15*16=11*13=14*6=3*7=4*10=12*1=8*9=2*6	AI EK
14	15*6=11*12=14*16=4*7=3*10=13*1=2*9=8*5	EG FI
15	8*16=2*6=11*4=12*7=13*10=3*1=15*9=14*5	– KM AO

Based on this analysis, the significant two-factor interactions in each of the IA sets of interest are:

- IA Set 5 - Either STMPxLOCA or FTMPxPREB
- IA Set 9 - Either FTMPxATMP or EXTNGTxBPRS
- IA Set 13 - Either FTMPxSTMP or CLEARxEXTNGT
- IA Set 14 - Either CLEARxFUEL or PREBxSTMP

The screening (or scree) plot of each factor's Sum of Squares as a percent of the total demonstrates the relative influences of different fire zone factors on quantities of extinguishant needed (Figure 4-1). Points indicated with numbers (e.g., IA Set 5) are two-factor interactions, rather than single factors. In all the scree plots that follow, "Effect Sum of Squares" refers to the contribution to the test measurement variability for each factor.

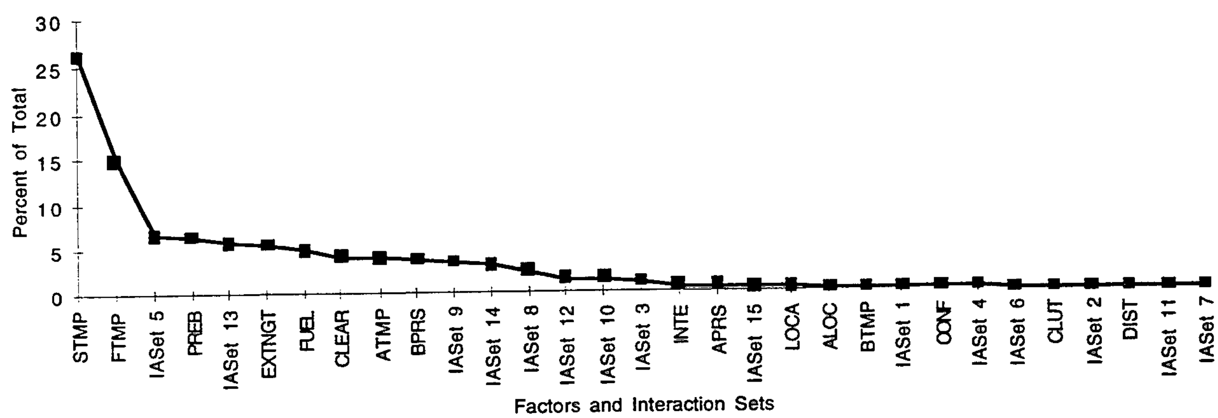

Figure 4-1. Effect Sum of Squares as Percent of Total

To further examine the data, a Normal Plot of the effects (a plot on Normal graph paper) was constructed. With this type of experimental design, there is no replication of experimental conditions to provide an estimate of experimental error. An analysis method often used to separate real effects from noise is a Normal Plot of the effects. Assuming that the data are approximately Normally distributed, the effects of the factors that have little or no influence on the response variable should plot as a straight line on the Normal Plot. Points that fall considerably off the line formed by the majority of plotted values suggest that those effects are having a stronger influence on the response variable. An examination of the Normal Plot, shown in Figure 4-2, clearly shows factors STMP, FTMP, PREB, CLEAR, and ATMP, and at the low end, FUEL, EXTNGT, and possibly BPRS are well off the line formed by the majority of points. All of these effects are statistically significant at the 0.05 level. This means there is a 95% probability that the identified factors do indeed have an effect on the weight of extinguishant required. The effects that appear to lie on the line are "pooled" into a term to estimate the experimental error and used in the analysis of variance. The plot also seems to indicate that perhaps some two-factor interactions are "off the line."

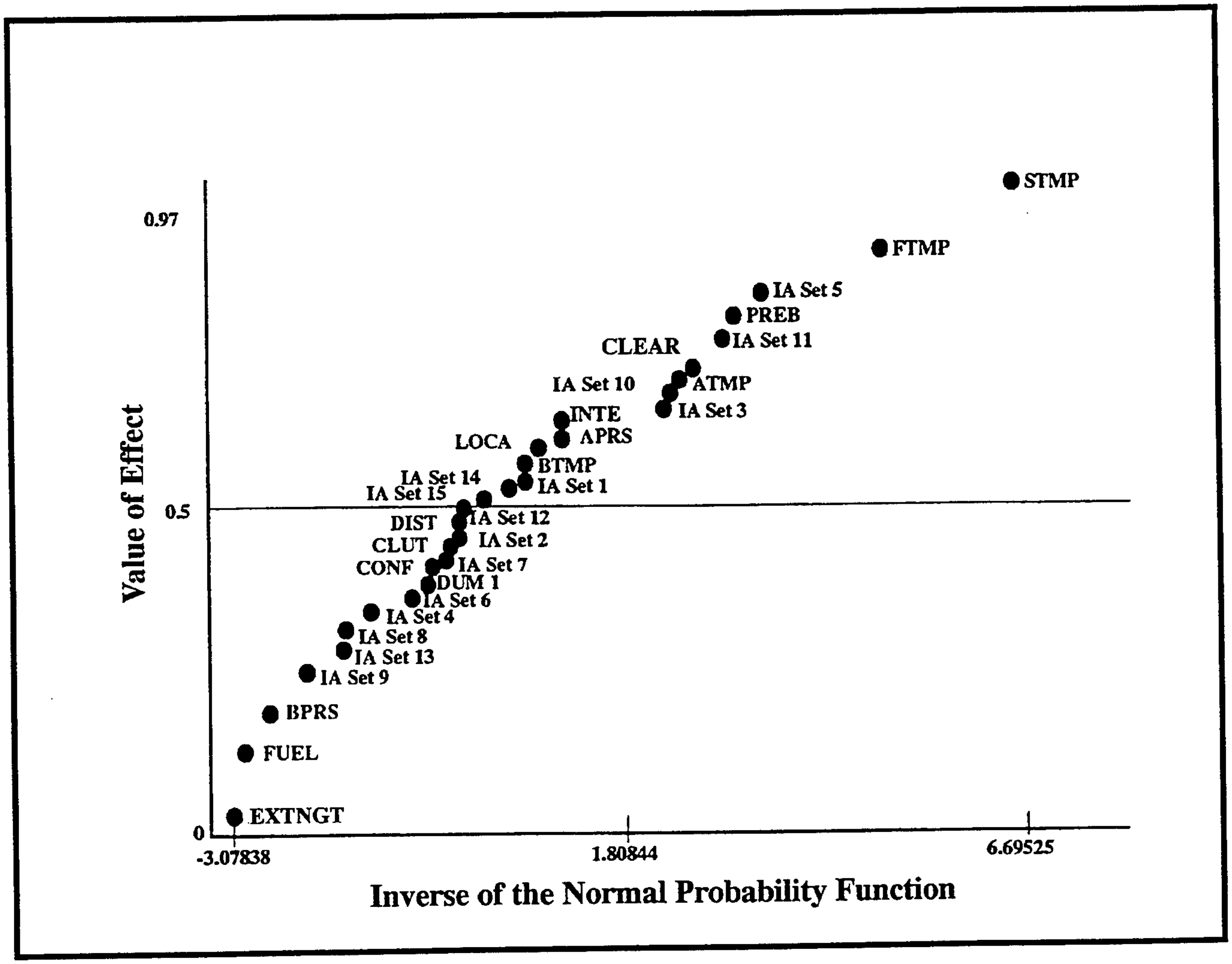

Figure 4-2. Normal Plot of the Effects

Table 4-8 presents a preliminary Analysis of Variance (ANOVA) for the Phase I test matrix results. In all the ANOVA tables that follow, the following abbreviations are used:

- D.F. - degrees of freedom describe the relative efficiency of the different estimators. Estimates vary more with fewer degrees of freedom.
- S.S. - sum of squares, calculated as the sum of the squared deviation of each observation from the mean.
- M.S. - mean square, calculated as the S.S. divided by the degrees of freedom. The greater the M.S., the greater the variance of the factor (parameter), and therefore, the more likely the factor has a statistically significant effect on the response variable (the amount of extinguishant required to extinguish a fire).
- F - F- ratio, calculated as the mean square for each factor (parameter) divided by the M.S. of the error term. When the F-ratio is close to 1.0, the estimates of the M.S. for a specific factor and the M.S. of the error are similar. This is an indication that the factor under consideration

probably does not have a significant effect on the response variable. However, when the F-ratio is large, the estimates are dissimilar, and this dissimilarity is taken to be an indication of potential real effect of the factor on the response variable. The F-ratio can also be thought of as discriminating between the real effects (signal) of each factor and statistical fluctuations (noise).

Table 4-8. Analysis of Variance - Phase I Test Matrix - Engine Nacelle

FACTOR	D. F.	S. S.	M. S.	F
STMP	1	358.611	358.611	48.10028
FTMP	1	206.634	206.634	27.7157
IA Set 5	1	91.7809	91.7809	12.31052
PREB	1	89.0579	89.0579	11.94528
IA Set 13	1	80.6895	80.6895	10.82284
EXTNGT	1	75.8111	75.8111	10.1685
FUEL	1	66.3149	66.3149	8.894779
CLEAR	1	59.2797	59.2797	7.951151
AIRT	1	54.8733	54.8733	7.360123
BPRS	1	52.5979	52.5979	7.054925
IA Set 9	1	49.935	49.935	6.697752
IA Set 14	1	44.5238	44.5238	5.971951
Error	19	141.6542411	7.455486374	
Total	31	1371.763241		

4.1.2 Transformation of the Response Variable

When performing an analysis of data, it is often the case that the data are better analyzed using a transformation of the response variable rather than the original metric in which the data are reported. Common statistical practice dictates an analysis of the data using a logarithm of the response variable should be considered when the range of the response data is large, typically an order of magnitude. Such was the case here.

To determine if a transformation of the data was needed, a plot of the residuals versus predicted values was constructed. The residual at each observation is defined as the observed response value minus the predicted response value. If the plot shows a purely random pattern about zero, a transformation is not indicated. Predicted values of the response variable were generated using a predictive model of the general form $\mathbf{Y = b_0 + b_1X_1 + b_2X_2 + ... + b_kX_k}$. Such a model can be fitted to the experimental conditions and used to generate predicted values. Here the X_i's are the factors (parameters), in their standard units and test values, that are judged to stand out from the "noise". The remaining effects are set equal to zero. For example, if the factors STMP, FTMP, PREB, EXTNGT, FUEL, CLEAR, ATMP, and BPRS were judged to stand out from the noise (see Figure 4-2), and the more likely interactions were selected from the interaction sets, a predictive model of the form

Predicted Amount of Extinguishant = 5.301995 - 0.0012514*STMP - 0.0371929*FTMP - 0.4009593*PREB - 2.0786543* EXTNGT - 2.1575296*FUEL + 0.4536875*CLEAR - 0.0008004*ATMP - 0.0064103*BPRS + 0.0023017*FTMP*PREB + 0.0000205*FTMP*STMP + 0.0000870*FTMP*ATMP + 0.0002796*PREB*STMP

was developed. Please note the b_0 and b_i values are based on model development with the factors (X's) in their standard units and test values, except for the factors EXTNGT and FUEL which used the coded values (-1/+1) for LOW and HIGH settings, respectively. Different values for b_0 and the b_i's would have been derived if coded values had been used for all the factors. A plot of the residuals versus predicted values was constructed and is shown in Figure 4-3. Negative predicted values are due to inaccuracies associated with the predictive model.

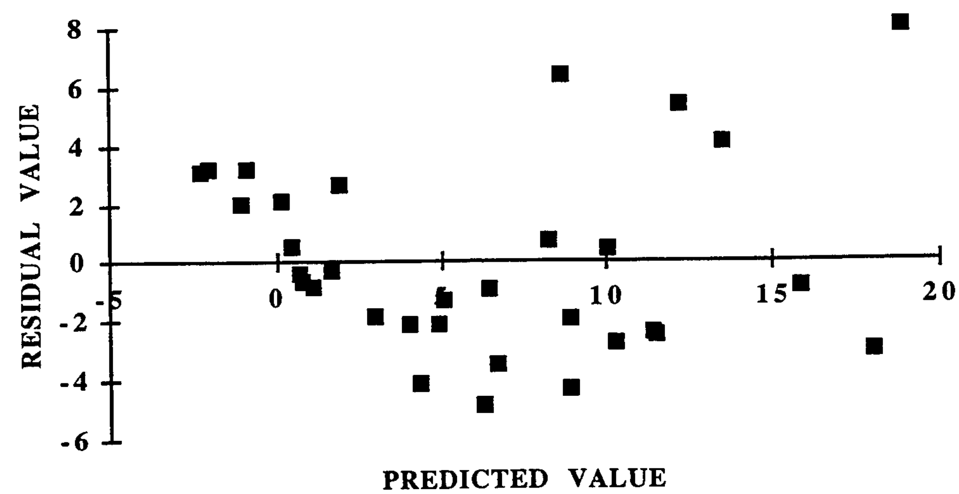

Figure 4-3. Residual Values Versus Predicted Values - Phase I

This plot does not show the characteristics of a random scatter about zero that would be expected if the underlying assumptions of the analysis were being satisfied. Rather, the plot indicates that an analysis should be considered using some transformation of the original response variable. Accordingly, a natural logarithmic transformation was performed and the data reanalyzed.

4.1.3 Analysis of the Factorial Experiment After Log Transformation

Table 4-9 shows the results of analysis of the factorial experimental data after performing a natural logarithmic transformation.

Those factors that were 3% or more of the total sum of squares were identified as variables to be included in the next phase of the experimentation. More typically, only those factors that are 5 to 10% of the total sum of squares would be identified as probably having an effect distinguishable from statistical noise. Since this was only the first phase of testing, it was decided to err on the conservative side and not exclude variables from future phases of the experiment.

Table 4-9. Analysis of the Factorial Experiment After Log Transformation

FACTOR	EFFECT	SUM OF SQUARES	PERCENT OF TOTAL
STMP	1.59655	20.3917	33.7784
EXTNGT	-1.04339	8.70932	14.4268
CLEAR	0.947613	7.18377	11.8997
IA Set 4	0.583619	2.72489	4.51371
IA Set 5	0.575816	2.65252	4.39383
IA Set 12	-0.56266	2.53268	4.19532
IA Set 13	0.540963	2.34113	3.87802
FTMP	0.482258	1.86059	3.08202
ATMP	-0.468527	1.75614	2.909
IA Set 3	-0.45738	1.67359	2.77227
LOCA	-0.40387	1.30488	2.1615
PREB	0.403451	1.30218	2.15703
IA Set 14	0.38573	1.1903	1.9717
IA Set 9	0.379103	1.14975	1.90454
IA Set 7	-0.30827	0.760247	1.25933
BPRS	-0.30546	0.746454	1.23648
APRS	0.284879	0.649249	1.07546
IA Set 2	-0.18884	0.285289	0.472575
FUEL	-0.18798	0.282704	0.468292
IA Set 1	0.158242	0.200325	0.331834
IA Set 6	-0.15384	0.189323	0.313609
BTMP	-0.11692	0.109364	0.181159
INTE	0.114186	0.104308	0.172784
IA Set 11	-0.10392	0.0863984	0.143117
DIST	0.09332	0.0696684	0.115404
CONF	0.06784	0.0368184	0.0609889
CLUT	-0.0642	0.0329712	0.054616
ALOC	0.052799	0.0223021	0.0369429
IA Set 8	-0.04839	0.0187344	0.0310331
IA Set 10	0.010678	0.000912179	0.001511
IA Set 15	0.008743	0.000611563	0.00101304
TOTAL		60.369119642	100.00%

With the transformation, those factors that are 3% or more of the total Sum of Squares are:

1. Surface Temperature (STMP) - 33.8%
2. Extinguishant (EXTNGT) - 14.4%
3. Clearance (CLEAR) - 11.9%
4. Fuel Temperature (FTMP) - 3.1%
5. Air Temperature (ATMP) - 2.9%
6. Two-factor interactions. The significant interaction sets are:
   - IA Set 4 - 4.5%
   - IA Set 5 - 4.4%
   - IA Set 12 - 4.2%
   - IA Set 13 - 3.9%

The same methodology used previously to investigate the pretransformed data (Paragraph 4.1.1) is repeated for the post-transformed. The factors studied in the interaction sets are given in Table 4-10.

Table 4-10. Confounded Two-factor Interaction Sets After Log Transformation - Engine Nacelle

INTERACTION SETS		INTERACTIONS	
IA Set 1		AB=CF=GH=EL=DK=MN=JO=IP	
IA Set 2		AC=DG=BF=HK=IO=EM=LN=JP	
IA Set 3		AD=CG=FH=IL=BK=JM=NO=EP	
IA Set 4		AE=GJ=IK=BL=CM=FN=HO=DP	
IA Set 5		BC=AF=DH=IJ=GK=LM=EN=OP	
IA Set 6		BD=CH=EI=FG=AK=JN=MO=LP	
IA Set 7		BE=DI=HJ=AL=FM=CN=GO=KP	
IA Set 8		CD=AG=BH=EJ=FK=IN=LO=MP	
IA Set 9		CE=DJ=HI=BN=FL=AM=KO=GP	
IA Set 10		DE=BI=CJ=KL=GM=HN=FO=AP	
IA Set 11		DF=BG=AH=CK=JL=IM=EO=NP	
IA Set 12		EF=GI=JK=CL=BM=AN=DO=HP	
IA Set 13		AI=EK=FJ=DL=HM=GN=CO=BP	
IA Set 14		AJ=EG=FI=HL=DM=KN=BO=CP	
IA Set 15		CI=BJ=EH=GL=KM=DN=AO=FP	
FACTORS			
A=FTMP	E=CLEAR	I=STMP	M=ATMP
B=CLUT	F=PREB	J=LOCA	N=DIST
C=INTE	G=FUEL	K=EXTNGT	O=BRPS
D=CONF	H=BTMP	L=AIRP	P=ALOC

Again, each of the main factors was ranked from 16 (largest effect) to 1 (smallest effect) based on each factor's percent of total sum of squares (see Table 4-9). The ranking of the factors is given in Table 4-11.

Table 4-11. Rankings of Factors After Log Transformation - Engine Nacelle

RANK NUMBER	FACTOR	RANK NUMBER	FACTOR	RANK NUMBER	FACTOR	RANK NUMBER	FACTOR
16	I	12	M	8	L	4	N
15	K	11	J	7	G	3	D
14	E	10	F	6	H	2	B
13	A	9	O	5	C	1	P

Next, each factor in an interaction was replaced by its rank number. Interaction IK, for example, would be replaced by 16*15, indicating that this interaction involves the two largest main effects. Those interactions with the largest product would be likely candidates to be the interactions that are the active ones. It is possible for two factors to have small main effects but still have a significant interaction. This means the combination of settings of two or more variables have a pronounced effect on the response variable. However, typically one of the interaction factors is significant as a main effect by itself to produce a significant two-factor interaction with another. The interaction groups are shown in Table 4-12.

Table 4-12. Interaction Groups After Log Transformation - Engine Nacelle

INTERACTION SET	INTERACTION PAIR WITH FACTOR REPLACED WITH RANK NUMBER IN THE ANALYSIS	MOST LIKELY INTERACTION COMBINATIONS
1	12*1=4*9=6*5=13*7=2*14=11*3=10*8=16*1	EL JO
2	12*4=2*6=1*9=5*14=15*8=13*11=7*3=11*1	IO EM
3	12*2=4*6=9*5=15*7=1*14=10*11=3*8=14*1	IL JM
4	12*13=6*10=15*14=1*7=4*11=9*3=5*8=3*1	AE IK
5	1*4=12*9=2*5=15*10=6*14=7*11=13*3=9*1	IJ AF
6	1*2=4*5=13*15=9*6=12*14=10*3=11*8=8*1	EI AK
7	1*13=2*15=5*10=12*7=9*11=4*3=6*8=15*1	AL FM
8	4*2=12*6=1*5=13*10=9*14=15*3=7*8=12*1	EJ FK
9	4*13=2*10=5*15=1*3=9*7=12*11=14*8=7*1	AM KO
10	2*13=1*15=4*10=14*7=6*11=5*3=9*8=13*1	KL FO
11	2*9=1*6=12*5=4*14=10*7=15*11=13*8=4*1	IM EO
12	13*9=6*15=10*14=4*7=1*11=12*3=2*8=6*1	EF JK
13	12*15=13*14=9*10=2*7=5*11=6*3=4*8=2*1	AI EK
14	13*6=9*15=14*8=5*7=2*11=14*3=1*8=5*1	FI AJ
15	4*15=1*10=13*5=6*7=14*11=2*3=12*8=10*1	KM AO

Based on this analysis, the significant two-factor interactions in each of the IA sets of interest are:

- IA Set 4 - Either EXTNGTxSTMP or FTMPxCLEAR
- IA Set 5 - Either STMPxLOCA or FTMPxPREB or AIRTxAIRP
- IA Set 12 - Either PREBxCLEAR or EXTNGTxLOCA
- IA Set 13 - Either FTMPxSTMP or EXTNGTxCLEAR or PREBxLOC

The scree plot of each factor's Sum of Squares as a percent of the total demonstrates the relative influences of different fire zone factors on quantities of extinguishing extinguishant needed (Figure 4-4).

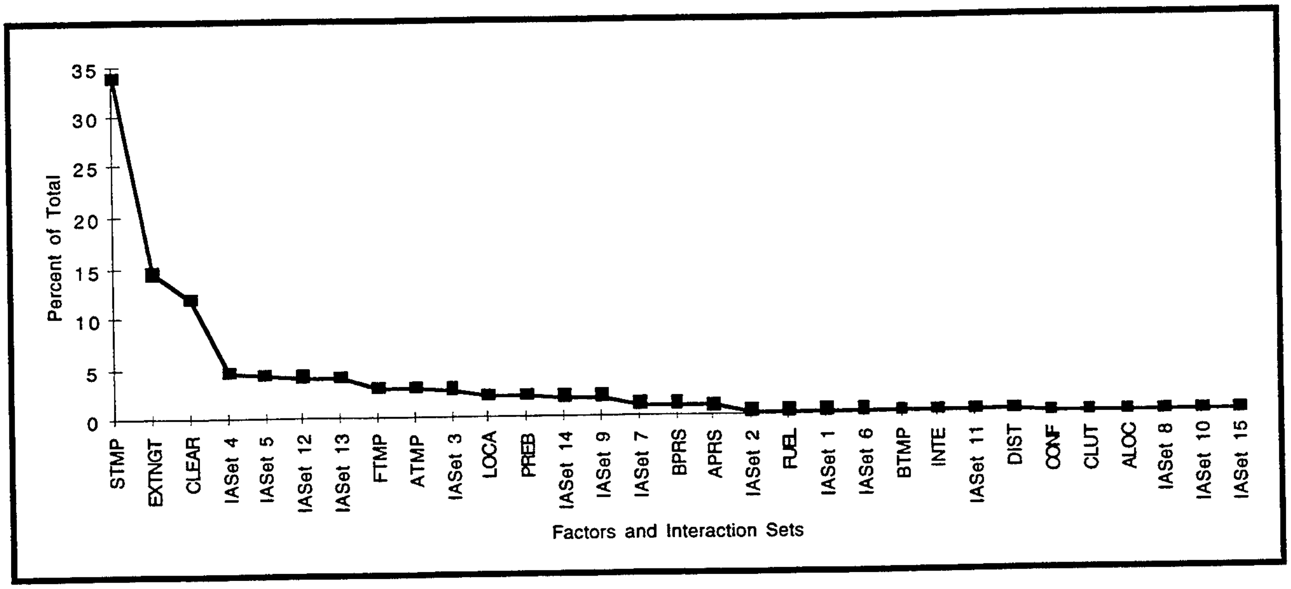

Figure 4-4. Effect Sum of Squares as Percent of Total After Log Transformation

A Normal Plot of the effects after the Log transformation was constructed. The results are shown in Figure 4-5. Now the Normal Plot is much more definitive. Only STMP, CLEAR, and EXTNGT are seen to stand out from the line formed by the other effects, as well as some two-factor interactions. This means that a change in the settings of these factors significantly affects the response variable - the amount of extinguishant required to extinguish the fire. Only these three effects have an influence on the response variable large enough to clearly stand out from the experimental error and are statistically significant at the 0.05 level. Less obvious are the factors FTMP and ATMP, each being approximately 3% of the Sum of Squares. The remaining effects are "pooled" into a term to estimate experimental error and used in the ANOVA results shown in Table 4-13.

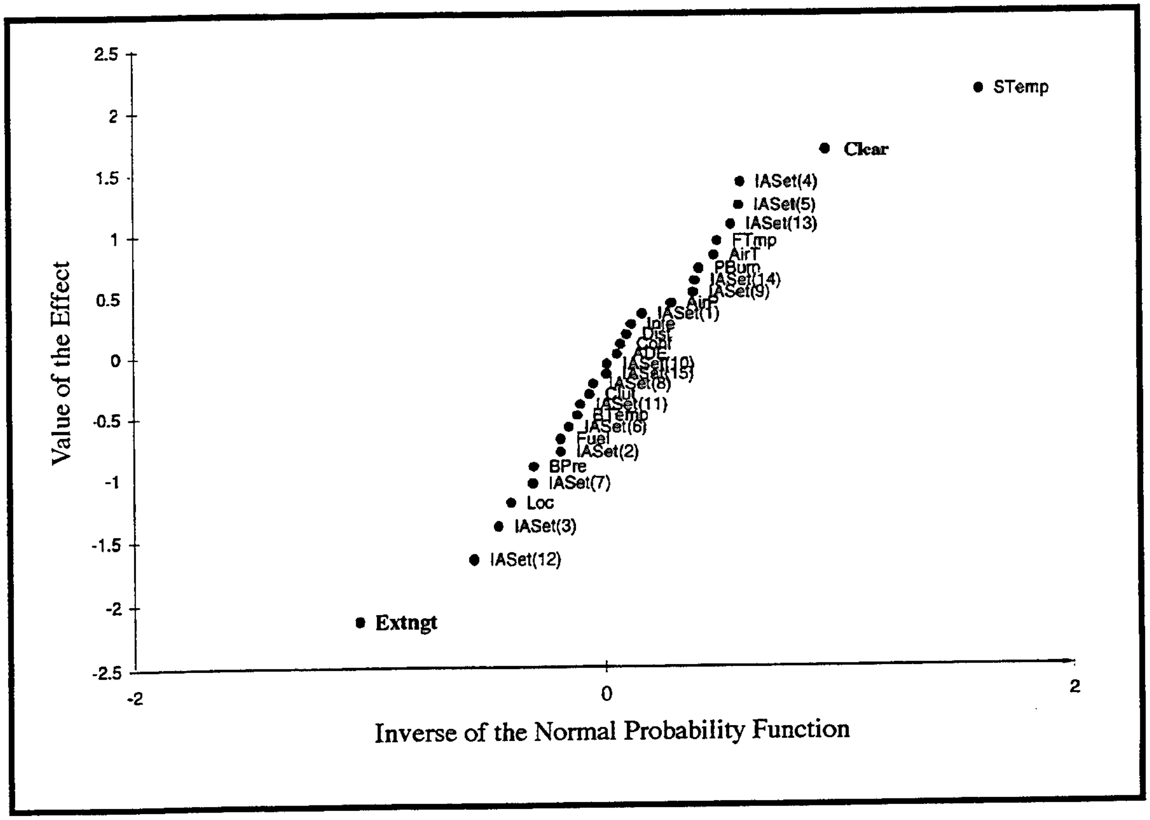

Figure 4-5. Normal Plot of the Effects After Log Transformation

Table 4-13. Analysis of Variance After Log Transformation - Phase I Test Matrix - Engine Nacelle

FACTOR	D. F.	S. S.	M. S.	F
STMP	1	20.3917	20.3917	43.91158274
EXTNGT	1	8.70932	8.70932	18.75469067
CLEAR	1	7.18377	7.18377	15.46956413
IA Set 4	1	2.72489	2.72489	5.86779095
IA Set 5	1	2.65252	2.65252	5.711949051
IA Set 12	1	2.53268	2.53268	5.453885031
IA Set 13	1	2.34113	2.34113	5.04140036
FTMP	1	1.86059	1.86059	4.006603262
ATMP	1	1.75614	1.75614	3.781680141
Error	22	10.21637964	0.464380893	
TOTAL	31	60.36911964		

Using the five factors presented in Table 4-13 above and selecting the most likely interactions from the interaction sets, a predictive model of the form

Ln(Predicted Amount of Extinguishant) = -1.1744833 + 0.0003465*STMP - 0.0020966*FTMP - 0.838772*EXTNGT + 0.1232584*CLEAR + 0.0026773*ATMP + 0.0003338*EXTNGT*STMP + 0.0000151*STMP*LOCA - 0.2813294*EXTNGT*LOCA + 0.0000059*FTMP*STMP

was developed and used to generate predicted values. A plot of residual values versus predicted values was made to check on the fit of the model, as shown in Figure 4-6. The residual plot now looks much more like a random scatter plot of points above zero. Negative predicted values are the result of a logarithmic transformation of a number less than 1 or inaccuracies associated with the predictions of the model.

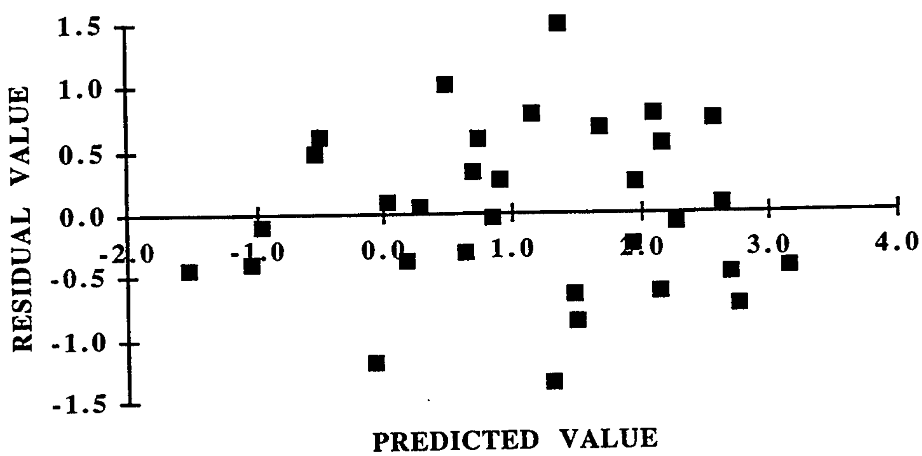

Figure 4-6. Residual Values Versus Predicted Values After Log Transformation - Phase I

4.2 Analysis Summary

The data analysis was performed on the original response variable (weight of extinguishant required to extinguish fire) and on the logarithm of the response variable. The conclusions were similar for both analyses. The three most important factors influencing the response were Surface Temperature, Extinguishant, and Clearance. With the transformed data, these three factors combined account for 60% of the variability of the response variable. The individual contributions are shown below:

- Surface Temperature - 33.8%
- Extinguishant - 14.4%
- Clearance - 11.9%

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the statistical analysis of the data generated under this test program and documented in this report, three factors in an aircraft engine nacelle fire most influence the amount of extinguishant needed to extinguish that fire. These three factors stand out as being statistically more significant than any other factor or interaction between two factors. These factors are:

- Surface Temperature
- Extinguishant
- Clearance

5.2 Recommendations

5.2.1 Phase II Test Parameters

A meeting of the Phase II Test Planning Working Group was held on August 3, 1994 to review the results of the 360° engine nacelle testing and to consider the factors to be used in Phase II testing. Based on the results of Phase I, participants recommended that the factors Surface Temperature, Extinguishant, and Clearance be included in the Phase II test matrix, as well as others based upon two-factor interactions and other predicted potential effects based upon the three extinguishants selected for testing in Phase II.

5.2.2 Reignition Phenomenon

It is recommended that the reignition phenomenon be studied in greater depth. Testing conducted during this phase of the overall test program has uncovered the problems associated with keeping a fire suppressed after the extinguishant has been discharged and fuel continues to impinge on hot surfaces. Post-discharge fuel flow time - the maximum length of time fuel can continue to flow after the release of the maximum amount of extinguishant available and still not have reignition - needs to be investigated in greater detail for various types of fuel.

6.0 REFERENCES

1. Little, Bennett, Lee, "Comprehensive Test Plan, Halon Replacement Program for Aviation," October 1992.

2. Ball, Robert E., "The Fundamentals of Aircraft Combat Survivability Analysis and Design," 1985.

3. National Institute of Standards and Technology NIST SP 861, "Evaluation of Alternative In-Flight Fire Suppressants for Full Scale Testing in Simulated Aircraft Engine Nacelles and Dry Bays," April 1994.

APPENDIX A

120° ANNULUS TEST FIXTURE QUALIFICATION TESTING

1. INTRODUCTION

During the period of May - August 1993, the L-32 Test Matrix developed for the engine nacelle application was run on the 120° annulus test fixture (one third of an engine nacelle) in the engine nacelle test facility at Wright-Patterson Air Force Base. Reasons for this test series were twofold:

- The 120° annulus fixture was initially the test fixture operational within the engine nacelle facility. While providing most of the capabilities necessary to conduct the test matrix, there were a number of shortfalls. The most significant of these was the fact that neither the clearance of the nacelle simulator nor the extinguishant discharge location could be varied. As a consequence, the test matrix parameters Clearance (CLEAR) and Extinguishant Discharge Location (ALOC) could not be varied while using this simulator. In addition, the representation of one third of an engine nacelle did not allow for realistic distribution of extinguishant in the fixture and during the test. Despite these shortcomings, the test matrix was run in order to insure that some data were available in the event that the full 360° annulus test fixture could not be installed and qualified in a time frame sufficient to allow for completion of the L-32 test matrix.

- Conduct of the test matrix on the 120° annulus provided valuable "lessons learned" for the test team to use when performing the test matrix on the 360° annulus.

2. DESCRIPTION

The 120° (1/3) annulus engine nacelle simulator was a two-radian sector of concentric cylinders. The inner cylinder had a 15-inch radius; the outer cylinder, 24-inches. This provided the simulator with a nominal clearance of 9 inches. Hot surface capabilities were provided by three heated sections with a total length of 37 inches. An unheated inlet section of approximately five feet, together with an inlet transition, provided uniform flow within the nacelle test section. The inlet section transitioned from a 24-inch diameter duct to the 9 inch clearance test section. The last of the three heated sections directed airflow into a 4-foot diameter plenum, which then transitioned into a 24-inch diameter exhaust duct. The test simulator could also be rotated, thereby allowing the establishment of fires in the top and bottom of the test simulator.

3. 120° ANNULUS TEST MATRIX

The parameters and level settings used in the 120° annulus test matrix are shown below in Table A-1. These parameters and their level settings are identical to those presented in Table 3-2 with the exception that Table A-1 does not contain the parameter Extinguishant Discharge Location (ALOC) and the level for the parameter Clearance (CLEAR) is constant for both the LOW and HIGH settings.

The test matrix is presented in Table A-2. All shots were made with CLEAR at 9 inches.

Table A-1. 120° Annulus Parameters and Settings

PARAMETERS	SYMBOL	LOW SETTING	HIGH SETTING
Extinguishant	EXTINGT	Perfluorohexane	Halon 1301
Extinguishant Distribution	DIST	Dump	Dist Tube
Extinguishant Temperature	BTMP	-20°F	160°F
Air Pressure	APRS	14.5 psia	17.0 psia
Air Temperature	ATMP	100°F	275°F
Bottle Pressure (non-adjusted)	BPRS	400 psi	800 psi
Clutter	CLUT	Low	High
Configuration	CONF	Short	Long
Clearance (distance between outer nacelle and engine core)	CLEAR	9 inches	9 inches
Fire Location (in nacelle)	LOCA	Bottom	Top
Fuel	FUEL	MIL-H-83282 hydraulic fluid	JP-8
Fuel Temperature	FTMP	100°F	200°F (83282) 325°F (JP-8)
Internal Ventilation Airflow	INTE	1.25 lb/s	2.75 lb/s
Preburn Time	PREB	5 sec	20 sec
Surface Temperature	STMP	175°F	1300°F

Table A-2. 120° Annulus Test Matrix

CONF	INTE (lb/s)	LOCA	CLUT	STMP (°F)	DIST	BTMP (°F)	PREB (sec)	BPRS (psia)	APRS (psia)	EXTNGT	ATMP (°F)	FUEL	FTMP (°F)	AMT (lbs)
Short	0.6	Bot	Low	175	Dump	-20	5	270	14.5	Perf	100	83282	100	1.125
Short	0.6	Bot	Low	175	Dump	-20	20	800	17.0	1301	260	JP-8	325	0.340
Short	0.6	Bot	High	1300	Tube	160	20	800	17.0	1301	100	83282	100	0.520
Short	0.6	Bot	High	1300	Tube	160	5	460	14.5	Perf	260	JP-8	325	0.815
Short	2.5	Top	High	1300	Dump	-20	5	400	17.0	1301	260	JP-8	100	0.280
Short	2.5	Top	High	1300	Dump	-20	20	540	14.5	Perf	100	83282	200	0.650
Short	2.5	Top	Low	175	Tube	160	20	1000	14.5	Perf	260	JP-8	100	5.295
Short	2.5	Top	Low	175	Tube	160	5	400	17.0	1301	100	83282	200	0.220
Long	2.5	Bot	Low	1300	Tube	-20	5	540	17.0	Perf	100	JP-8	325	1.950
Long	2.5	Bot	Low	1300	Tube	-20	20	400	14.5	1301	260	83282	100	1.840
Long	2.5	Bot	High	175	Dump	160	20	400	14.5	1301	100	JP-8	325	0.385
Long	2.5	Bot	High	175	Dump	160	5	1000	17.0	Perf	260	83282	100	0.750
Long	0.6	Top	High	175	Tube	-20	5	800	14.5	1301	260	83282	200	0.165
Long	0.6	Top	High	175	Tube	-20	20	270	17.0	Perf	100	JP-8	100	7.765
Long	0.6	Top	Low	1300	Dump	160	20	460	17.0	Perf	260	83282	200	31.19
Long	0.6	Top	Low	1300	Dump	160	5	800	14.5	1301	100	JP-8	100	0.330
Long	0.6	Bot	Low	175	Tube	160	5	400	17.0	1301	260	JP-8	100	0.315
Long	0.6	Bot	Low	175	Tube	160	20	1070	14.5	Perf	100	83282	200	0.690
Long	0.6	Bot	High	1300	Dump	-20	20	620	14.5	Perf	260	JP-8	100	2.625
Long	0.6	Bot	High	1300	Dump	-20	5	400	17.0	1301	100	83282	200	3.150
Long	2.5	Top	High	1300	Tube	160	5	460	14.5	Perf	100	83282	100	0.630
Long	2.5	Top	High	1300	Tube	160	20	800	17.0	1301	260	JP-8	325	22.00
Long	2.5	Top	Low	175	Dump	-20	20	800	17.0	1301	100	83282	100	0.510
Long	2.5	Top	Low	175	Dump	-20	5	270	14.5	Perf	260	JP-8	325	0.675
Short	2.5	Bot	Low	1300	Dump	160	5	800	14.5	1301	260	83282	200	0.113
Short	2.5	Bot	Low	1300	Dump	160	20	460	17.0	Perf	100	JP-8	100	0.850
Short	2.5	Bot	High	175	Tube	-20	20	270	17.0	Perf	260	83282	200	3.400
Short	2.5	Bot	High	175	Tube	-20	5	800	14.5	1301	100	JP-8	100	0.090
Short	0.6	Top	High	175	Dump	160	5	1000	17.0	Perf	100	JP-8	325	0.810
Short	0.6	Top	High	175	Dump	160	20	400	14.5	1301	260	83282	100	0.260
Short	0.6	Top	Low	1300	Tube	-20	20	400	14.5	1301	100	JP-8	325	0.220
Short	0.6	Top	Low	1300	Tube	-20	5	540	17.0	Perf	260	83282	100	28.57

4. ANALYSIS OF THE 120° NACELLE TEST MATRIX

The data were analyzed to calculate effect size and sum of squares for each factor and interaction between factors, as shown in Table A-3. The sum of squares for each factor was then expressed as a percent of total Sum of Squares, or total variability. The larger the percentage of total variability accounted for by any factor, the stronger the indication from the data that the effect of that factor on the response variable is of sufficient size to stand out from the experimental error, or "noise."

Table A-3. Analysis of the Factorial Experiment for 120° Annulus

FACTOR	EFFECT	SUM OF SQUARES	PERCENT OF TOTAL
APRS	5.4195	234.968	11.9586
LOCA	5.0383	203.072	10.3353
IA Set 12	4.9705	197.647	10.0592
ATMP	4.9211	193.74	9.8603
IA Set 4	4.7414	179.845	9.1532
STMP	4.5586	166.248	8.4612
IA Set 5	3.9626	125.619	6.3936
EXTNGT	-3.5658	101.717	5.1768
IA Set 13	-2.8843	66.5512	3.3871
INTE	-2.4533	48.1475	2.4505
IA Set 6	-2.4351	47.4387	2.4144
IA Set 8	-2.428	47.1615	2.4002
PREB	2.4095	46.4455	2.3638
IA Set 11	2.1168	35.845	1.8243
IA Set 15	1.9989	31.964	1.6268
CONF	1.9633	30.8348	1.5693
DIST	1.9026	28.9599	1.4739
CLUT	-1.8711	28.0089	1.4255
IA Set 7	1.8674	27.8967	1.4198
FUEL	-1.8149	26.3502	1.3411
IA Set 2	1.4549	16.9333	0.8618
IA Set 10	1.4068	15.8316	0.8057
IA Set 1	1.3683	14.9769	0.7622
IA Set 14	-1.2876	13.2638	0.6751
DUM1	1.2164	11.8365	0.6024
FTMP	0.9386	7.0481	0.3587
BPRS	0.768	4.7186	0.2402
BTMP	0.7386	4.3645	0.2221
DUM2	0.7055	3.9818	0.2027
IA Set 3	0.5976	2.8573	0.1454
IA Set 9	0.267	0.5703	0.0290
TOTAL		1964.84	100.00%

Those factors and two-factor interactions that are each 4% or more of the total Sum of Squares are:

1. Air Pressure (APRS) - 12.0%
2. Fire Location (LOCA) - 10.3%
3. Air Temperature (ATMP) - 9.9%
4. Surface Temperature (STMP) - 8.5%
5. Extinguishant (EXTNGT) - 5.2%
6. Two-factor interactions

Those factors that were 4% or more of the total sum of squares were identified as probably having an effect distinguishable from statistical noise. More typically, only those factors that are greater than 5 to 10 percent of the total would be identified as having a significant effect. However, at this stage of experimentation, it was decided to err on the conservative side and not exclude variables from possible future phases of experimentation.

The scree plot of each factor's Sum of Squares as a percent of the total demonstrates the relative influences of different fire zone factors on quantities of extinguishant needed (Figure A-1).

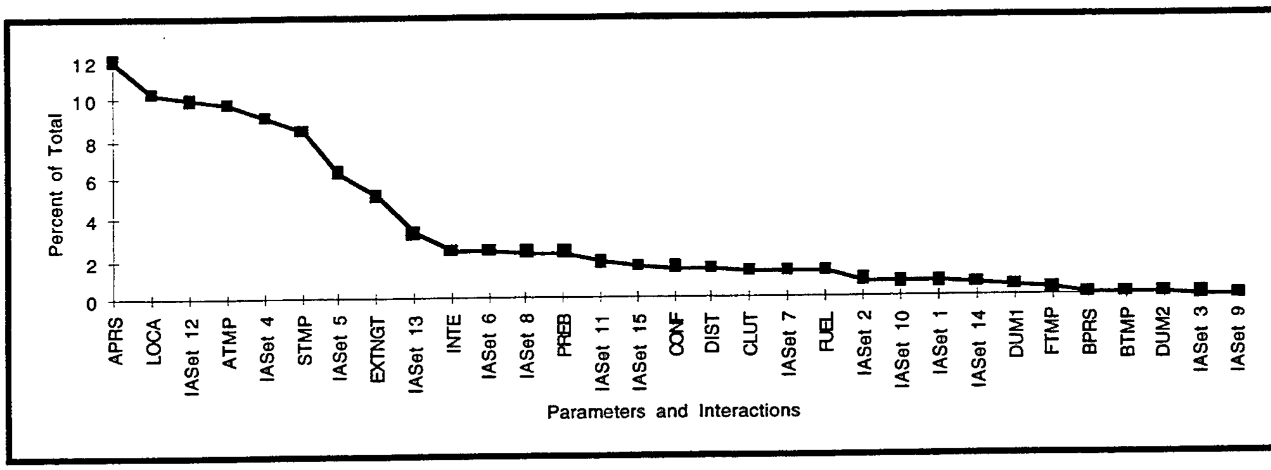

Figure A-1. Effect Sum of Squares as Percent of Totalfor 120° Annulus

The remaining factors and interactions were "pooled" into a term to provide an estimate of the experimental error. This pooling was used in the analysis of variance (ANOVA) data shown in Table A-4.

Table A-4. ANOVA for 120° Annulus

FACTOR	D. F.	S. S.	M. S.	F
APRS	1	234.968	234.968	9.616
LOCA	1	203.072	203.072	8.311
IA Set 12	1	197.647	197.647	8.089
ATMP	1	193.74	193.74	7.929
IA Set 4	1	179.845	179.845	7.360
STMP	1	166.248	166.248	6.804
IA Set 5	1	125.619	125.619	5.141
EXTNGT	1	101.717	101.717	4.163
Error	23	561.987	24.434	
Total		1964.84		

4.1 Transformation of the Response Variable

When performing an analysis of data, it is often the case that the data are better analyzed using a transformation of the response variable rather than the original metric in which the data are reported. Common statistical practice dictates an analysis of the data using a logarithm of the response variable should be considered when the range of the data is large, typically an order of magnitude.

To determine if a transformation of the data was needed, a plot of the residuals versus predicted values was constructed. If the plot shows a purely random pattern about zero, a transformation is not indicated. Predicted values of the response variable were generated using a predictive model of the general form $\mathbf{Y=b_0+b_1X_1+b_2X_2+...+b_kX_k}$. Such a model can be fitted to the experimental conditions and used to generate predicted values. Here the X_i's are the coded values (-1 for the LOW setting and +1 for the HIGH setting) of the effects that are judged to stand out from the "noise", b_0 is the mean of all the response data, and the b_i coefficient for each effect in the model is one-half the effect for that variable. The remaining effects are set equal to zero. For example, if the factors APRS, LOCA, ATMP, STMP, and AGNT are judged to stand out from the noise, a predictive model of the form

Predicted Value of Extinguishant = 3.704 + 2.710*APRS + 2.519*LOCA + 2.461*ATMP + 2.279*STMP - 1.783*EXTNGT + 1.981*STMP*LOCA + 2.371*LOCA *ATMP + 2.485*STMP*ATMP

was developed. The interactions shown in the model were selected from their respective interaction sets based on the fact that they are composed of factors which individually are considered significant. Please note that the b_0 and b_i values are based on model development with the coded values (-1/+1). Different values would have been derived if actual data had been used. A plot of the residuals versus predicted values was constructed and is shown in Figure A-2.

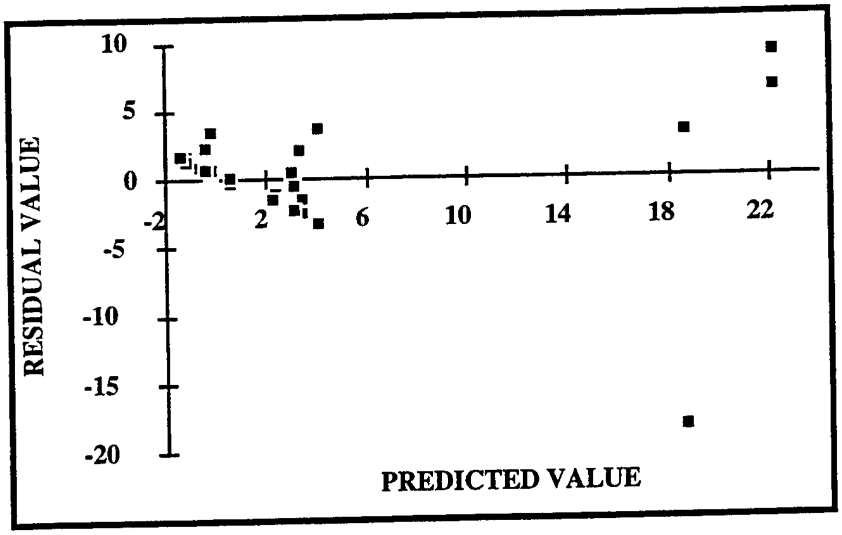

Figure A-2. Residual Values Versus Predicted Values for 120° Annulus

This plot does not show the characteristics of a random scatter about zero that would be expected if the underlying assumptions of the analysis were being satisfied. Rather, the plot indicates that an analysis should be considered using some transformation of the original response variable. Accordingly, a natural logarithmic transformation was performed and the data reanalyzed.

4.2 Analysis of the Factorial Experiment After Log Transformation

Table A-5 shows the results of analysis of the factorial experimental data after performing a natural logarithmic transformation.

Table A-5. Analysis of the Factorial Experiment After Log Transformation for 120° Annulus

FACTOR	EFFECT	SUM OF SQUARES	PERCENT OF TOTAL
EXTNGT	-1.486	17.6649	24.4324
APRS	1.1112	9.8784	13.6629
PREB	0.8484	5.7577	7.9635
STMP	0.7763	4.8213	6.6683
IA Set 15	0.7159	4.0999	5.6706
CONF	0.7113	4.0476	5.5982
ATMP	0.6943	3.8562	5.3336
IA Set 1	0.6792	3.6906	5.1045
IA Set 4	0.6307	3.1819	4.4009
IA Set 12	0.5954	2.8358	3.9222
LOCA	0.4748	1.8032	2.494
DIST	0.4379	1.5341	2.1218
IA Set 7	0.4201	1.412	1.9529
IA Set 13	-0.4082	1.333	1.8437
IA Set 6	0.3763	1.1328	1.5668
IA Set 11	0.3633	1.0559	1.4604
IA Set 14	0.3551	1.0085	1.3949
IA Set 2	0.3321	0.8823	1.2202
INTE	-0.3192	0.8149	1.1271
DUM1	0.2338	0.4375	0.6051
BTMP	-0.186	0.2766	0.3826
IA Set 3	-0.1727	0.2385	0.3298
IA Set 5	0.1385	0.1535	0.2123
FUEL	-0.137	0.1501	0.2076
IA Set 9	0.1232	0.1215	0.168
CLUT	-0.0788	0.0496	0.0687
BPRS	-0.0669	0.0358	0.0495
IA Set 8	-0.0369	0.0109	0.015
IA Set 10	-0.0347	-0.0096	0.0133
DUM2	-0.0214	0.0037	0.0051
FTMP	-0.0196	0.0031	0.0043
TOTAL		78.2822	100.00%

With the transformation, those factors and two-factor interactions that are 4% or more of the total Sum of Squares are:

1. Extinguishant (EXTNGT) - 24.4%
2. Air Pressure (APRS) - 13.7%
3. Preburn Time (PREB) - 8.0%
4. Surface Temperature (STMP) - 6.7%
5. Configuration (CONF) - 5.6%
6. Air Temperature (ATMP) - 5.3%
7. Two-factor interactions

Following the methodology for determining the most likely interactions in each of the two-factor interaction sets (in Section 4.1.1 and 4.1.3), the most likely interactions are:

IA Set 15 - STMP*CONF or PREB*ATMP,
IA Set 1 - CONF*EXTNGT or INTE*PREB, and
IA Set 4 - STMP*APRS or LOCA*ATMP.

Figure A-3 shows the screening (or scree) plot of the Sum of Squares as a percent of the total for each factor and two-factor interaction sets following log transformation.

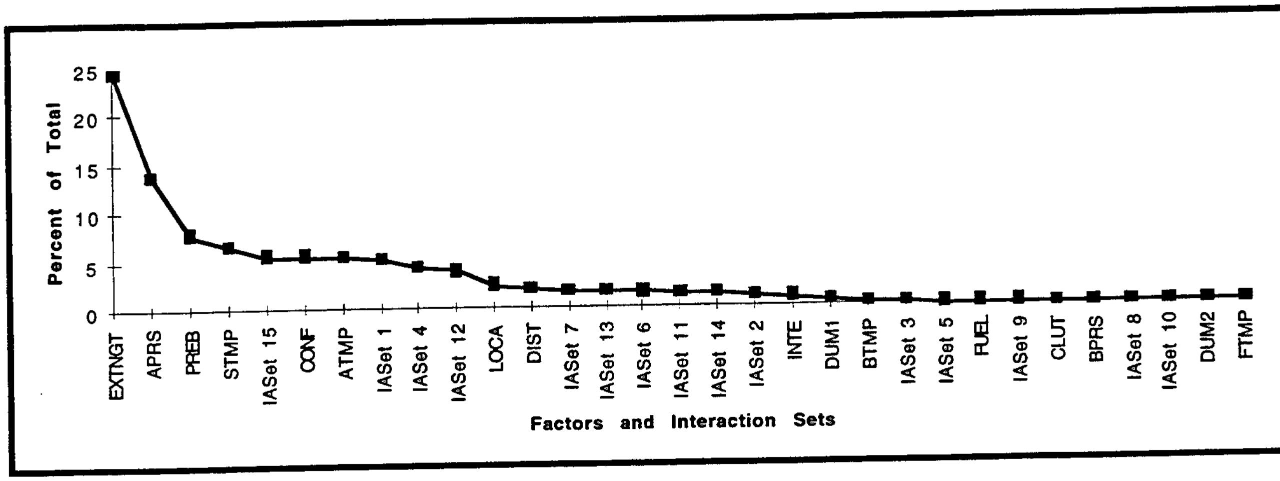

Figure A-3. Effect Sum of Squares as Percent of Total After Log Transformation for 120° Annulus

The remaining effects are "pooled" into a term to estimate experimental error for use in the ANOVA results shown in Table A-6.

Table A-6. ANOVA After Log Transformation for 120° Annulus

FACTOR	D. F.	S. S.	M. S.	F
EXTNGT	1	17.6649	17.6649	29.7556
APRS	1	9.8784	9.8784	16.6397
PREB	1	5.7577	5.7577	9.6986
STMP	1	4.8213	4.8213	8.1212
IA Set 15	1	4.0999	4.0999	6.9060
CONF	1	4.0476	4.0476	6.8179
ATMP	1	3.8562	3.8562	6.4956
IA Set 1	1	3.6906	3.6906	6.2166
IA Set 4	1	3.1819	3.1819	5.3597
IA Set 12	1	2.8358	2.8358	4.7767
Error	21	12.448	0.5928	
TOTAL	31	72.2822		

A plot of residuals versus predicted values was made to check on the fit of the model, as shown in Figure A-4 below. A predictive model of the form

Ln(Predicted Value of Extinguishant) = -0.058 - 0.743*EXTNGT + 0.556*APRS + 0.424*PREB + 0.388*STMP +0.356*CONF + 0.347*ATMP + 0.340*CONF*EXTNGT + 0.315*LOCA *ATMP + 0.298*STMP* ATMP + 0.358*PREB*ATMP

was developed and used to generate the predicted values. The residual plot in Figure A-4 now looks much more like a random scatter plot of points about zero than the previous residual plot (Figure A-2).

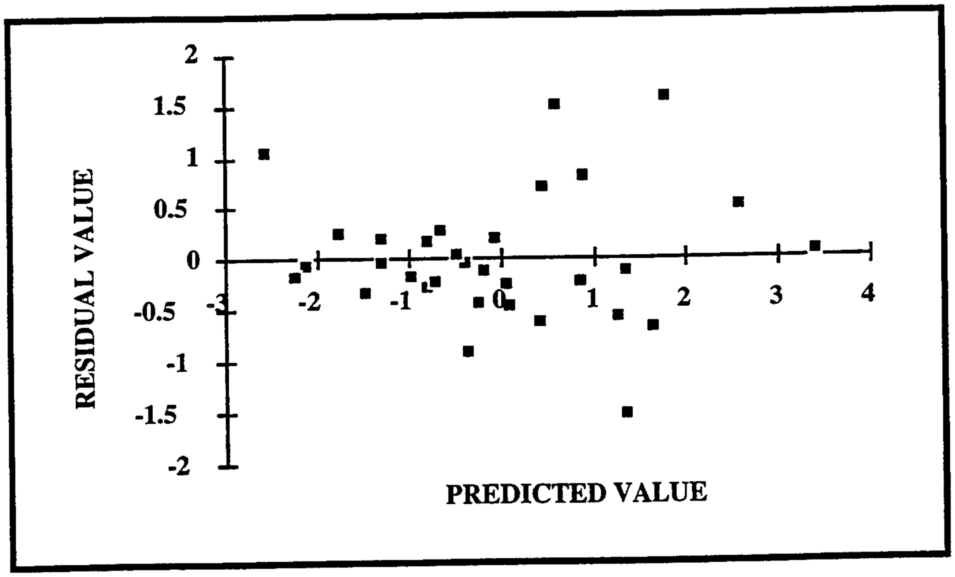

Figure A-4. Residual Values Versus Predicted Values After Log Transformation for 120° Annulus

5. CONCLUSIONS AND COMPARISONS

Based on the 120° annulus, and using the logarithmically transformed data, the following parameters were shown to have the greatest impact on fire extinguishment.

1. Extinguishant (EXTNGT) - 24.4%
2. Air Pressure (APRS) - 13.7%
3. Preburn Time (PREB) - 8.0%
4. Surface Temperature (STMP) - 6.7%
5. Configuration (CONF) - 5.6%
6. Air Temperature (ATMP) - 5.3%

The importance of obtaining the full 360° annulus and running the test matrix on it is demonstrated when the results of the two test series are compared. For the 360° nacelle, using transformed data, the following parameters were shown to be most significant:

1. Surface Temperature (STMP) - 33.8%
2. Extinguishant (EXTNGT) - 14.4%
3. Clearance (CLEAR) - 11.9%

Utilizing the 360° annulus has also introduced the parameter Clearance as significant. This parameter could not be varied in the 120° nacelle fixture. Inclusion of this parameter will allow the test program to more closely reflect the operational world. Using the full annulus also reordered the remaining two parameters.

The 120° test fixture was a moderately old piece of equipment. As a result, the seams of the 120° test fixture had a tendency to leak, pulling air in at atmospheric conditions, and blowing air out at higher pressures. This could have been a factor in explaining the significance in APRS for the 120° fixture and lack of APRS significance in the 360° fixture. The surface temperature simulation of the 120° fixture was much cruder and had limited controlled heating to the region directly under the fuel spray. The heaters had to radiate heat to the underside of the fixture and some losses and dissipation of heat would occur. The direct heating on the exterior of the engine casing at the site of the fire resulted in a larger contribution to the results in the new fixture.

APPENDIX B

POWDER EXTINGUISHANT TESTING

1. INTRODUCTION

Aircraft engine nacelle powder extinguishant testing occured from 7-28 September 1993. Originally it was intended to repeat a 32-run matrix for powder extinguishants to determine if additional factors were important in the effectiveness of powder extinguishants. From the originally designed L-32 test matrix developed for the engine nacelle application, only three test runs were completed, due to time constraints and concerns raised by the initial test results. These shots strongly validated the comments of aircraft maintenance specialists who recommended against the use of powder extinguishants in the engine nacelle because of cleanup considerations. Their reasoning was that the post-incident cleanup would be an overwhelming task. This would be crucial if the incident occurred when aircraft availability was critical, such as during the quick turn-around necessary for repeated aircraft sortie operations. In addition, false alarm discharges would require the same overwhelming cleanup.

2. APPROACH

An effort was made to keep the parameters in the powder extinguishant matrix as much like those in the gaseous extinguishant matrix as possible. However, due to differences in the delivery of the extinguishant, some changes were necessary. Again, extensive testing was performed to ensure that a sustainable fire could be achieved under every set of conditions and that the fire could be extinguished. Table B-1 lists the parameters chosen for the powder extinguishant phase and the settings for each level.

Table B-1. Powder Extinguishant Test Parameters and Levels for 120° Annulus

PARAMETER	LABEL	LOW SETTING	HIGH SETTING
Extinguishant	EXTNGT	Magnesium Oxide	Desi-Karb
Extinguishant Distribution	DIST	Dump	Tube
Extinguishant Pressure, (psia)	BPRS	600	800
Air Pressure, (psia)	APRS	14.7	17
Air Temperature, (°F)	ATMP	100	260
Dessicant Concentration (% by wt)	CABO	1	2
Clutter	CLUT	Low	High
Fire Location	LOCA	Bottom	Top
Fixture Length	LGTH	Short	Long
Fuel	FUEL	83282	JP-8
Fuel Temperature (°F), 83282	FTMP	100	200
Fuel Temperature (°F), JP-8	FTMP	100	325
Internal Ventilation Airflow (lb/sec)	INTE	0.6	2.5
Particle Size, (microns), Desi-Karb	PSIZ	20	40
Particle Size, (microns), MgO	PSIZ	2	10
Preburn Time (seconds)	PREB	5	20
Surface Temperature (°F)	STMP	175	1300

The two extinguishants that were chosen for powder testing were sodium bicarbonate (Desi-Karb) and Magnesium Oxide (MgO). These powders were mixed with 1% or 2% (by mass) fumed silica dessicant (Cabo-Sil). The dessicant was necessary to ensure proper flow of the powder through the extinguisher and the nacelle. Large and small particle sizes (PSIZ) were chosen for each extinguishant (40 microns and 20 microns for Desi-Karb; 10 microns and 2 microns for MgO). Sodium bicarbonate and magnesium oxide were selected as powder extinguishant corollaries to Halon 1301 and Perfluorohexane; sodium bicarbonate has a chemical suppression contribution, while for magnesium oxide, the effectiveness is purely physical in nature.

3. PROCEDURES

Except for changes made in the extinguishant handling, the procedures for the powder test series were identical to those used in the gaseous extinguishant test series. In the gaseous extinguishant test series, extinguishant was simply forced into the extinguisher through a flexible line. However, this method was impractical for powder extinguishants. To prevent packing of the extinguishant in the delivery system, Cabo-Sil fumed silica was mixed with the extinguishant.

4. TOXICITY

Though neither Desi-Karb nor MgO are toxic, some special handling was necessary. Since both extinguishants are powder and since they are mixed with a fumed silica dessicant, some respiratory problems can result from repeated exposure. Respirator masks were used during prolonged exposure, such as during charging of the extinguisher and cleanup after an experiment.

5. RESULTS

Three test runs were accomplished with powder extinguishants. Table B-2 shows the original test matrix for the powder extinguishants. As with the gaseous extinguishants, a bracketing procedure was used to arrive at the amount of powder extinguishant required to extinguish the fire. Each test run consisted of four individual tests in accordance with the established bracketing procedure. Table B-3 shows the resulting extinguishant amounts which were required to extinguish the fire under each set of test conditions. As before, the error in the final amount is ±6.5%. Due to the minimal amount of data generated from this test series, little can be discerned about the effect of each parameter on the effectiveness of the extinguishant.

Table B-2. Powder Test Matrix for 120° Annulus

RUN	CABO	LGTH	LOCA	CLUT	STMP	DIST	FUEL	FTMP	EXTNGT	PSIZ	BPRS	PREB	INTE	ATMP	APRS
1	1%	Short	Bottom	Low	175	Dump	83282	100	MgO	2	600	5	0.6	100	14.5
2	1%	Short	Bottom	Low	175	Dump	JP-8	325	DSC	20	800	20	0.6	260	17.0
3	1%	Short	Bottom	High	1300	Tube	83282	100	DSC	40	800	20	0.6	100	17.0
4	1%	Short	Bottom	High	1300	Tube	JP-8	325	MgO	10	600	5	0.6	260	14.7
5	1%	Short	Top	High	1300	Dump	JP-8	100	DSC	20	600	5	2.5	260	17.0
6	1%	Short	Top	High	1300	Dump	83282	200	MgO	2	800	20	2.5	100	14.5
7	1%	Short	Top	Low	175	Tube	JP-8	100	MgO	10	800	20	2.5	260	14.5
8	1%	Short	Top	Low	175	Tube	83282	200	DSC	40	600	5	2.5	100	17.0
9	1%	Long	Bottom	Low	1300	Tube	JP-8	325	MgO	2	800	5	2.5	100	17.0
10	1%	Long	Bottom	Low	1300	Tube	83282	100	DSC	20	600	20	2.5	260	14.5
11	1%	Long	Bottom	High	175	Dump	JP-8	325	DSC	40	600	20	2.5	100	14.5
12	1%	Long	Bottom	High	175	Dump	83282	100	MgO	10	800	5	2.5	260	17.0
13	1%	Long	Top	High	175	Tube	83282	200	DSC	20	800	5	0.6	260	14.5
14	1%	Long	Top	High	175	Tube	JP-8	100	MgO	2	600	20	0.6	100	17.0
15	1%	Long	Top	Low	1300	Dump	83282	200	MgO	10	600	20	0.6	260	17.0
16	1%	Long	Top	Low	1300	Dump	JP-8	100	DSC	40	800	5	0.6	100	14.5
17	2%	Long	Bottom	Low	175	Tube	JP-8	100	DSC	40	600	5	0.6	260	17.0
18	2%	Long	Bottom	Low	175	Tube	83282	200	MgO	10	800	20	0.6	100	14.5
19	2%	Long	Bottom	High	1300	Dump	JP-8	100	MgO	2	800	20	0.6	260	14.5
20	2%	Long	Bottom	High	1300	Dump	83282	200	DSC	20	600	5	0.6	100	17.0
21	2%	Long	Top	High	1300	Tube	83282	100	MgO	10	600	5	2.5	100	14.5
22	2%	Long	Top	High	1300	Tube	JP-8	325	DSC	40	800	20	2.5	260	17.0
23	2%	Long	Top	Low	175	Dump	83282	100	DSC	20	800	20	2.5	100	17.0
24	2%	Long	Top	Low	175	Dump	JP-8	325	MgO	2	600	5	2.5	260	14.5
25	2%	Short	Bottom	Low	1300	Dump	83282	200	DSC	40	800	5	2.5	260	14.5
26	2%	Short	Bottom	Low	1300	Dump	JP-8	100	MgO	10	600	20	2.5	100	17.0
27	2%	Short	Bottom	High	175	Tube	83282	200	MgO	2	600	20	2.5	260	17.0
28	2%	Short	Bottom	High	175	Tube	JP-8	100	DSC	20	800	5	2.5	100	14.5
29	2%	Short	Top	High	175	Dump	JP-8	325	MgO	10	800	5	0.6	100	17.0
30	2%	Short	Top	High	175	Dump	83282	100	DSC	40	600	20	0.6	260	14.5
31	2%	Short	Top	Low	1300	Tube	JP-8	325	DSC	20	600	20	0.6	100	14.5
32	2%	Short	Top	Low	1300	Tube	83282	100	MgO	2	800	5	0.6	260	17.0

Table B-3. 120° Annulus Powder Test Results

Run	Extinguishant	Part. Size (microns)	X1 (lbs)	X2 (lbs)	X3 (lbs)	X4 (lbs)	Amt (lbs)
1	MgO	2					
2	DSC	20					
3	DSC	40					
4	MgO	10					
5	DSC	20					
6	MgO	2					
7	MgO	10					
8	DSC	40					
9	MgO	2					
10	DSC	20					
11	DSC	40					
12	MgO	10					
13	DSC	20	.1	0.05	0.08	0.09	0.085
14	MgO	2					
15	MgO	10					
16	DSC	40					
17	DSC	40					
18	MgO	10					
19	MgO	2					
20	DSC	20					
21	MgO	10					
22	DSC	40					
23	DSC	20					
24	MgO	2	1.6	0.8	1.2	1.0	0.9
25	DSC	40					
26	MgO	10					
27	MgO	2					
28	DSC	20					
29	MgO	10					
30	DSC	40	0.8	1.2	1.0	1.1	1.15
31	DSC	20					
32	MgO	2					